Advances in Energy Storage Technologies and their Implementation into NASA Planetary Missions

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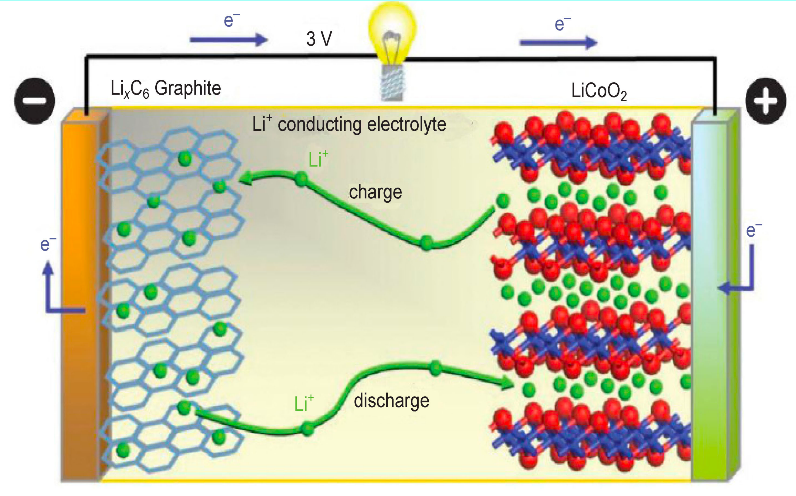
Energy Storage Systems (Basics)

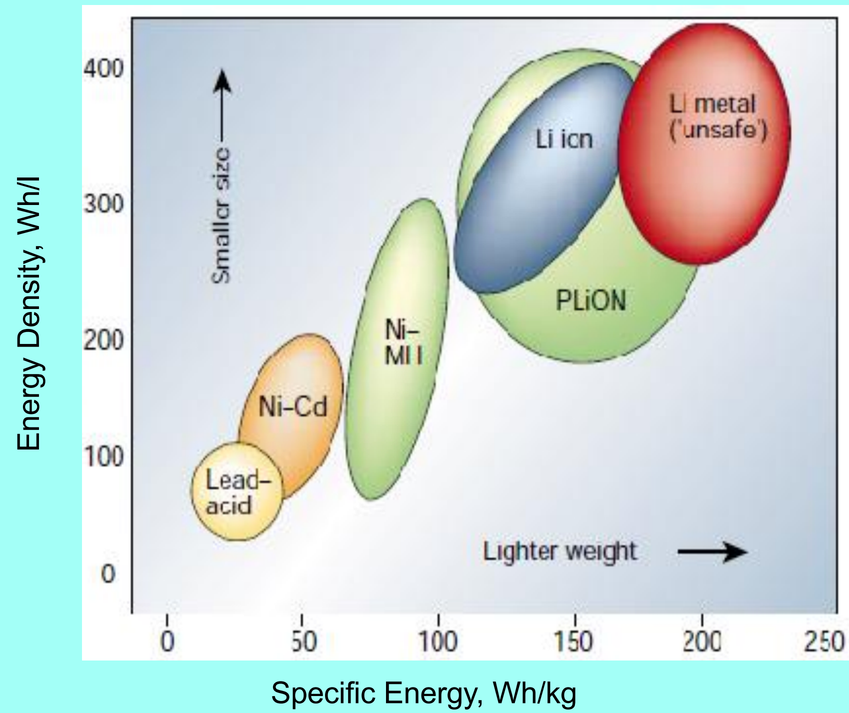
- Primary cells: Non-rechargeable
  - Irreversible cell reactions and One time use
  - Used in planetary Probes and Small rovers such as Huygens Probe
- Secondary cells: Rechargeable *(will mostly cover this category)*
  - Reversible cell reactions; Multiple uses (Discharge and charge cycles)
  - Used in Orbiters and Landers such as Mars Reconnaissance Orbiter or Mars Rovers
- Fuel cells
  - Non-rechargeable reactants that are replenished as they are consume
  - Hydrogen- oxygen fuel cells on Gemini, Apollo and Space Shuttle (Coupled with H_2 propellants and life support O_2)
- Capacitors
  - Charge separation across double layer or with the use of a dielectric layer (No electrochemical reactions)
  - Used for burst power applications (load-leveling), e.g., Cassini



- Electrochemical cell converts chemical energy into electrical energy

Battery Performance Metrics

Characteristic	Definition
Cell Voltage, V	Cathode potential minus anode potential ($E_{cathode}$-E_{anode})
Capacity, Ah	Total coulombs
Cell Energy, Wh	Product of voltage and Capacity
Power , W	Product of voltage and Current
Specific energy, Wh/kg	Energy per unit mass, Wh/kg
Energy Density, Wh/l	Energy per unit volume; Wh/l
Cycle life, #	Number of charge discharge cycles till the capacity drops below 80% of the initial value
Shelf life (Calendar life), years	Duration of storage period till the capacity drops below 80% of the initial value
Depth of Discharge, %	Extent to which the battery is discharged

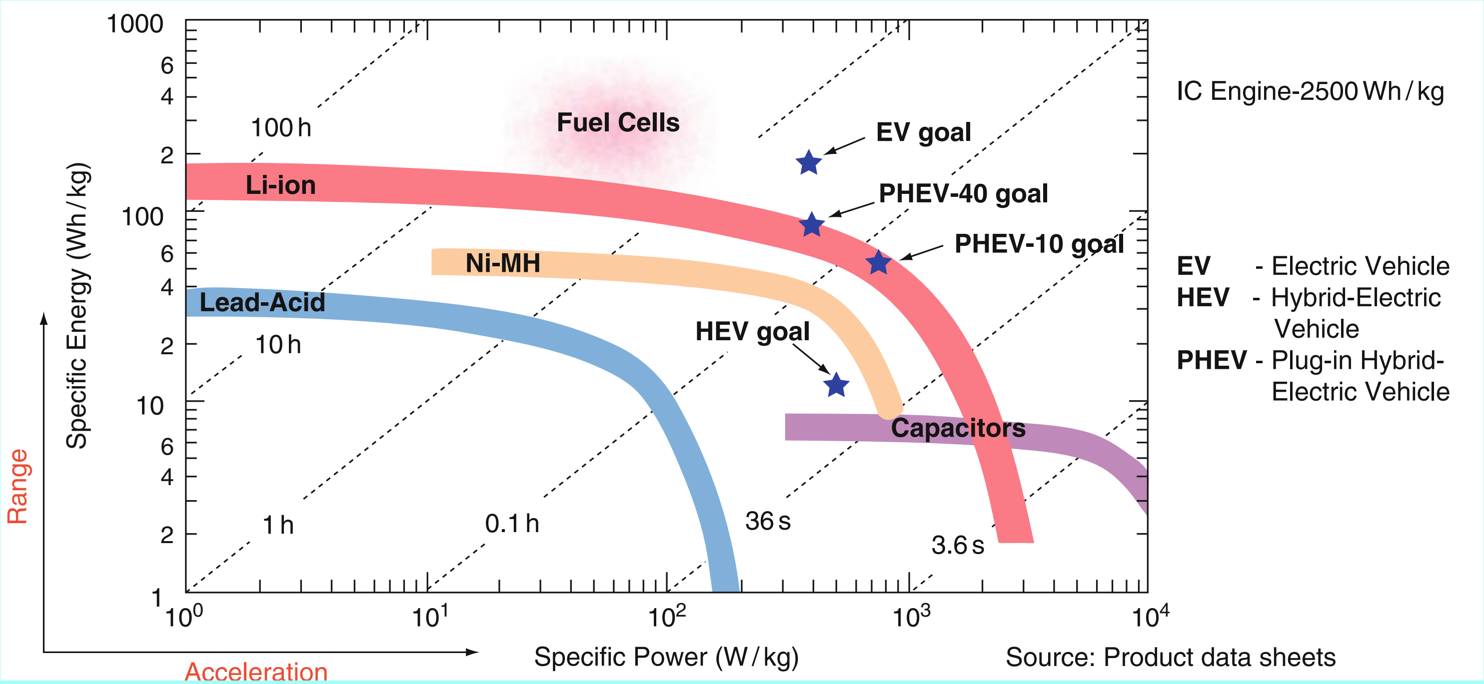


- Desired attributes
  - Lightweight, compact, long calendar life, Shelf Life, ~~Low cost~~, Safe
  - More payload (Science) and extended mission

Quote from Thomas Edison: "Just as soon as a man gets working on the secondary battery, it brings out his latent capacity for lying."

Categorization of Electrochemical Devices

Ragone Plot

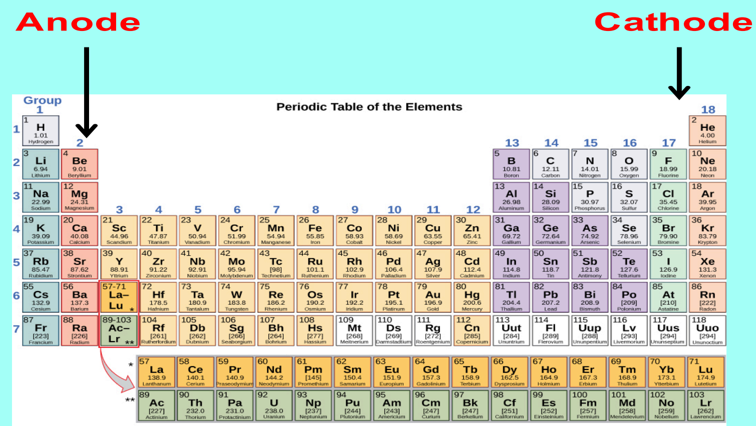


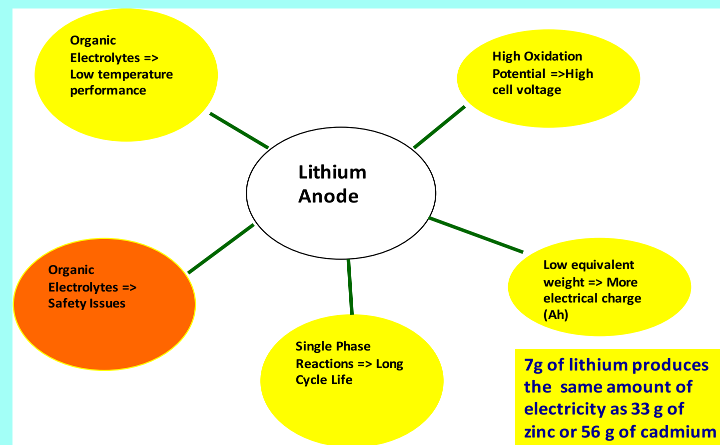
Source: DoE Reports

- Fuel Cells- Suitable for large Systems (100 kWh)
- Batteries: High energy and medium Power (max power 2-3 kW/kg)
- Capacitors: High Power (10 kW/kg) and low energy (5-10 Wh/kg)

Why Lithium Batteries?

- Highest oxidation potential (3.0 V vs. SHE)
  - High cell voltage when combined with many cathodes (3-5 V)
- Low equivalent weight
  - High specific capacity : 3.8 Ah/g
- High energy densities
- Small Ionic size
  - Intercalation into many cathodes with rapid diffusion. Excellent cycle life.
- Requires Non-aqueous electrolytes
  - Extends the cell voltage (beyond 2.0V)
  - Liquids even at low temperatures (wide operating temperatures).
  - Pose safety issues (flammable electrolytes)
- Sensitive to moisture
  - Requires cells to be hermetically sealeed

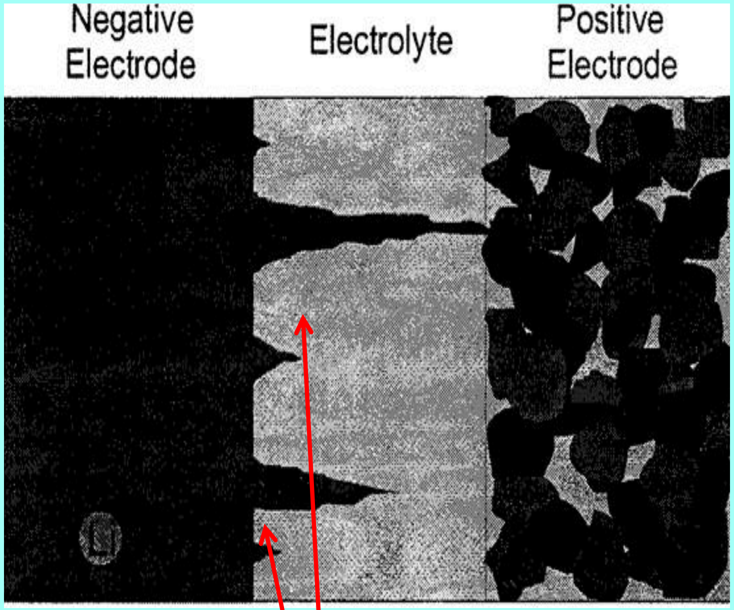




High specific energy, high energy density, long life and wide-operating temperature are possible with a Li battery

Li-Based Rechargeable Batteries
(Pre-Lithium Ion Era)

- Research between 1975 through 1991 focused on Li metal anode based systems (Not as widespread as today)
  - Several Li-insertion cathodes and stable electrolytes were developed at various laboratories (Bell Labs, Exxon, Honeywell, JPL)
    - TiS_2, $NbSe_3$, V_6O_{13}, MoS_2 Cathodes
    - 2Me-THF with LiAsF6 and 1,2 Dioxolane with $LiClO_4$ electrolytes
  - Good cycle life (>500 cycles) and high specific energy (>150 Wh/kg) were realized in laboratory cells, but were also accompanied by frequent early cell failures and safety issues
- *<u>Safety</u> was a serious concern*
  - *Lithium deposits as dendrites causing internal shorts and catastrophic cell failures*
  - *Still a challenge to find a stable electrolyte for Li anode*

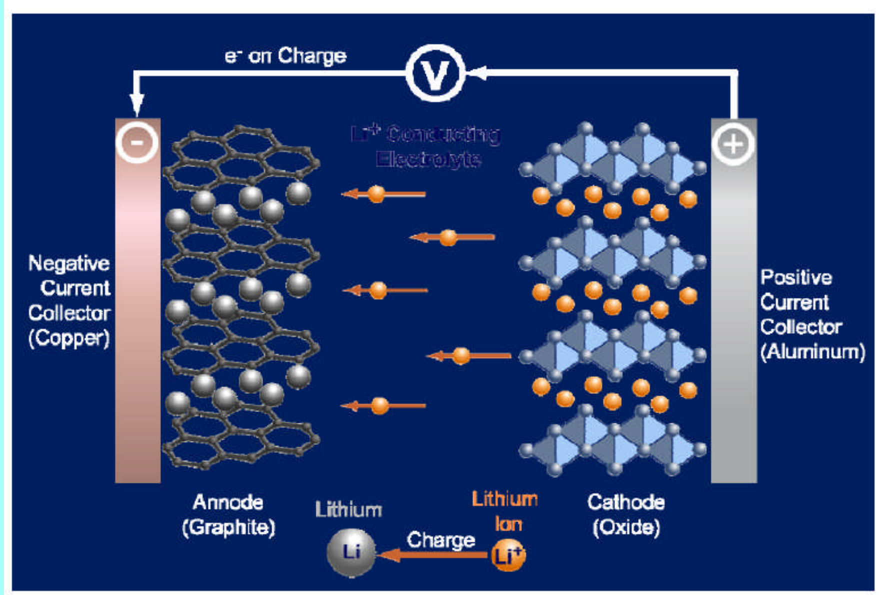


Lithium dendrites during the cycling of Li cell causing shorting

Renewed interested Li based rechargeable cells to improve energy densities

The Birth of Lithium-Ion Battery (1991)

- AT&T studied the intercalation of lithium in carbon (graphite Intercalation compounds) at low potentials (<0.8V)
- Goodenough (Oxford) reported the reversible lithiation and delithiation of cobalt oxide at high voltage (4.2 V).
- Early studies with propylene carbonate based solutions were not favorable because of its co-intercalation and ex-foliation of graphite
- Sony came out with the breakthrough technology combining coke (anode) with lithium cobalt oxide
  - First Li-ion cell (~70Wh/kg) -better than the best available aqueous system (Nickel-metal hydride) – a big boost to the portable electronics and vice versa
  - Cells can be assembled in discharged state without handling LI
  - Lithium-ion shuttles from cathode to anode (during discharge) and vice versa on charge; Hence the name lithium-ion (also called rocking chair!)
  - Lot safer than Li metal based systems, if properly operated



Schematic of a lithium-Ion cell

The key is the surface film on the graphite anode (termed as Solid Electrolyte Interface (SEI), which provides kinetic stability for the electrolyte

Several new (chemistry) variants emerged since with great improvement in energy densities

Multiple Chemistries for Lithium- Ion Cells

Anodes

- Carbon Anodes:
  - Coke
  - Graphite: (natural and synthetic)
  - Hard carbon,
  - Mesocarbon micro-bead (MCMB);
  - Surface Modified Graphite
- Lithium titanate
- Li Alloys and composites
  - Si
  - Sn

Electrolytes

- **Organic (Liquid) Electrolytes (Linear and cyclic carbonates, blends, co-solvents**
- **Gel Polymer electrolyte with liquid contained in polymer gels (PAN, PVDF)**
- **Solid Polymer (PEO type) electrolytes**
- **Solid State (LiPON, Garnet)**
- Ionic Liquids (??)

Cathodes

Metal Oxides (layered)

- **$LiCoO_2$**
- **$LiNo_{0.8}Co_{0.2}O_2$**
- **$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$**
- **$LiNi_{0.33}Co_{0.33}Mn_{0.33}O_2$**

Metal Oxides (Spinel)

- **$LiMn_2O_4$ (Spinel)**
- **$LiMn_{1.5}Ni_{0.5}O_2$**

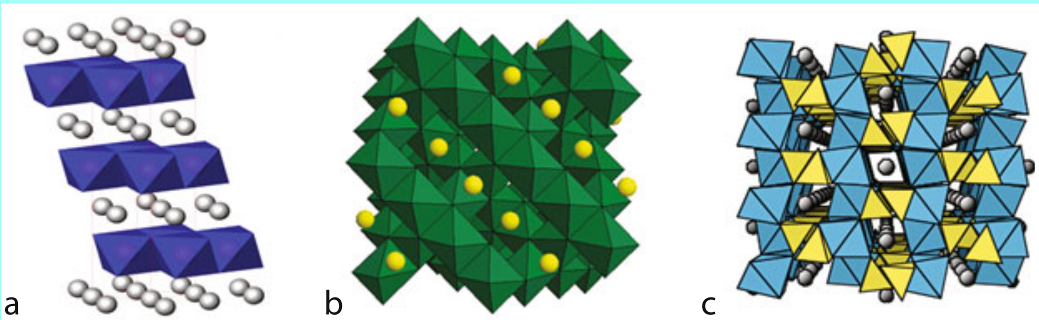
Metal Phosphates

$LiFePO_4$

- **$LiMnPO_4$,**
- **$LiCoPO_4$**
- **Conversion Cathodes (FeF_3), S**

Performance characteristics are specific to the combination anode, cathode and electrolyte

Li-ion Battery Cathodes

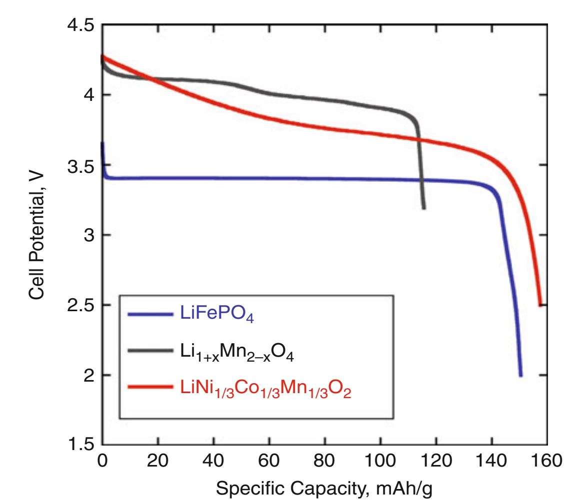


Layered Structure $LiCoO_2$ **Cubic structure of $LiMn_2O_4$ spinel** **Olivine structure of $LiFePO_4$**

Characteristics of Cathode Materials

Material	Structure	Potential versus Li/Li^+, average V	Specific capacity, mAh/g	Specific energy, Wh/kg
$LiCoO_2$	Layered	3.9	140	546
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)	Layered	3.8	180–200	680–760
$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ (NMC)	Layered	3.8	160–170	610–650
$LiMn_2O_4$ and variants (LMO)	Spinel	4.1	100–120	410–492
$LiFePO_4$ (LFP)	Olivine	3.45	150–170	518–587

Cathode		Advantages	Disadvantages	Applications
LiCoO2	LCO	In common use, good cycle life, good energy	Moderate charged state thermal stability,	Mainly smaller portable electronics (3C)
LiMn2O4	LMO	Excellent thermal stability and power capability, inexpensive	Moderate cycle life, lower energy	High power (power tools and electric motive power)
LiNi0.8Co0.15O2	NCA	Very good energy, good power capability, good cycle life	Moderate charged state thermal stability	Excellent for EV and premium electronic devices
LiNIxMnyCo1-x-yO2	NMC	Very good mix of energy, power, life and thermal stability	Patent issues	Both portable and high power (power tools and Evs)
LiFePO4	LFP	Very good thermal stability and cycle life, good power capability	Lower energy, special synthetic conditions	Mainly used in power tools and Grid storage

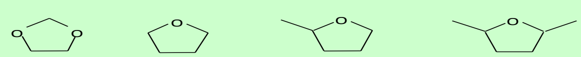
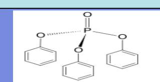


Anodes and Electrolytes in Li-ion Cells

Anodes in Li-ion Cells

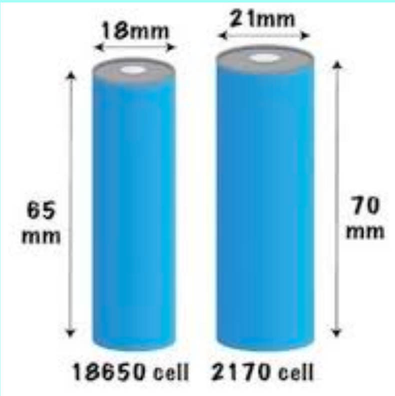
Anode	Specific Capacity	Voltage, V	TRL	Comments
MCMB/ Graphite	320	0.1	7-9	Baseline
Li Alloys (Li-Sn, Li-Si)	800-1000 mAh/g	0.5	3-4	Poor cycle life due to volume expansion upon alloying.
SnO_x	800	0.5	2-3	Huge Irreversible capacity; Limited cycling due to volume dilation and degradation
Li metal	1900 (50% efficiency)	0	1-2	Difficult chemistry in terms of safety, durability and reliability. Needs development in electrolytes

Electrolytes in Li-ion Cells

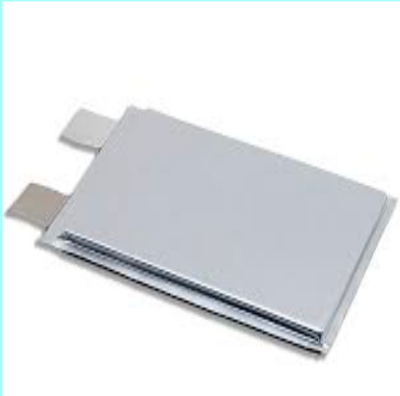
Chronology	System	Electrolyte Solvents	Electrolyte Salts
1980-1990	Li metal based system	Cyclic Ethers  1,3-Dioxolane (DIOX); Tetrahydrofuran (THF); 2-Methyltetrahydrofuran (2-MeTHF); 2,5-Dimethyltetrahydrofuran (2,5-DiMeTHF)	$LiAsF_6$, $LiClO_4$
1990--2000	Li-Ion	Carbonates  thylene carbonate (EC); Propylene carbonate (PC); Dimethyl carbonate (DMC); Diethyl carbonate (DEC)	$LiPF_6$
1990--2016	Low-tempearture Li-Ion	Esters  Methyl formate; Ethyl formate; Methyl acetate; Ethyl acetate	$LiPF_6$
2006-2015	Advanced Li-ion with enhanced safety	 Fluoroethylene carbonate (FEC);  Triphenyl phosphate (TPP)	$LiPF_6$, $LiBF_4$ LiBOB

Commercial and Custom-made Cell

COTS (Commercial)



Popular cell (18650)



Pouch cell (LiPO cell)

Large format (custom-made)

Flat-plate Prismatic

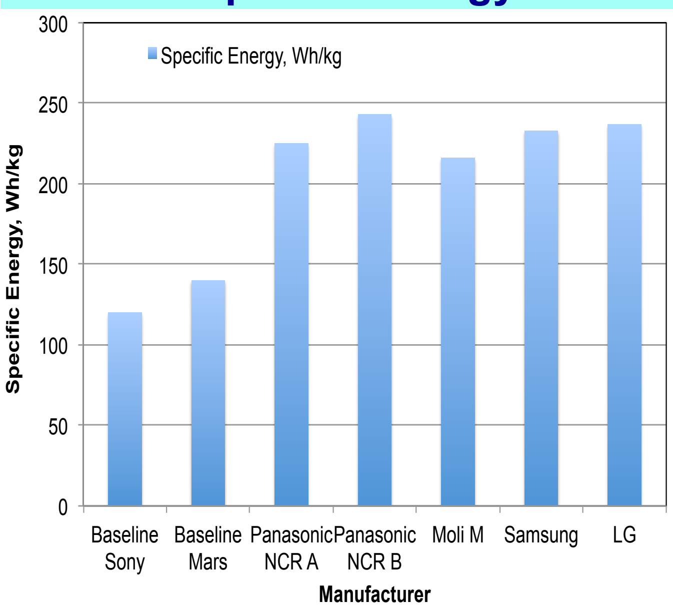
Cylindrical (5-200 Ah)

- Small 18650 cells have built-in safety devices: PTC (current limit), CID (Current Interrupt, pressure-based) and Vent
- Large cells have vents
- All cells have shut-down separator (tri-layer PE-PP)

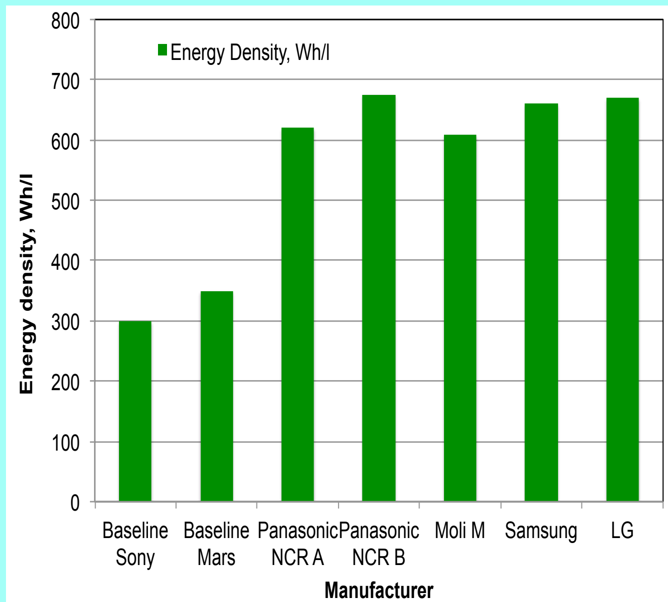
Commercial Cells are Continuing to Get Better

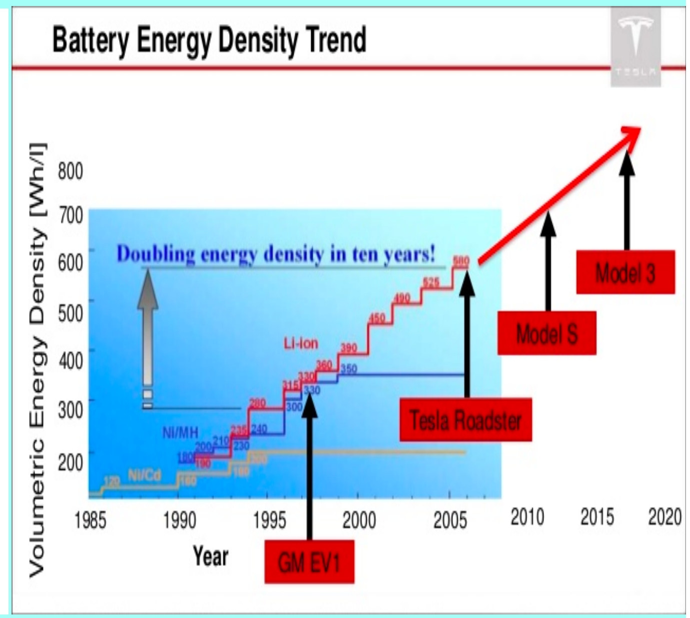
- Commercial manufacturers have traditionally focused on small cells (cylindrical 18650 cells and pouch cells).
- With improved cell designs (dense electrodes, thin separators), many commercial manufacturers have achieved significant energy improvements.

Specific Energy



Energy Density

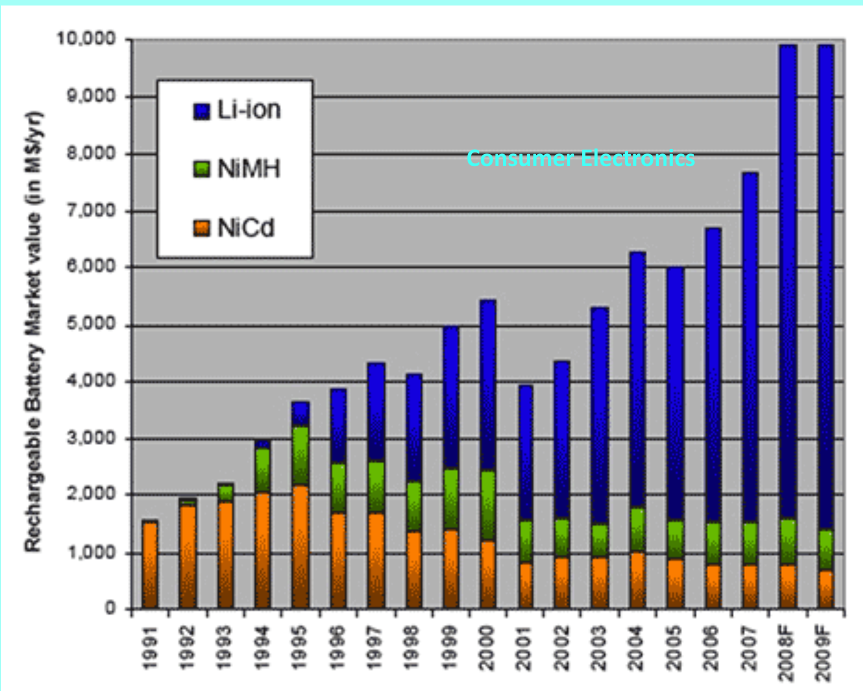


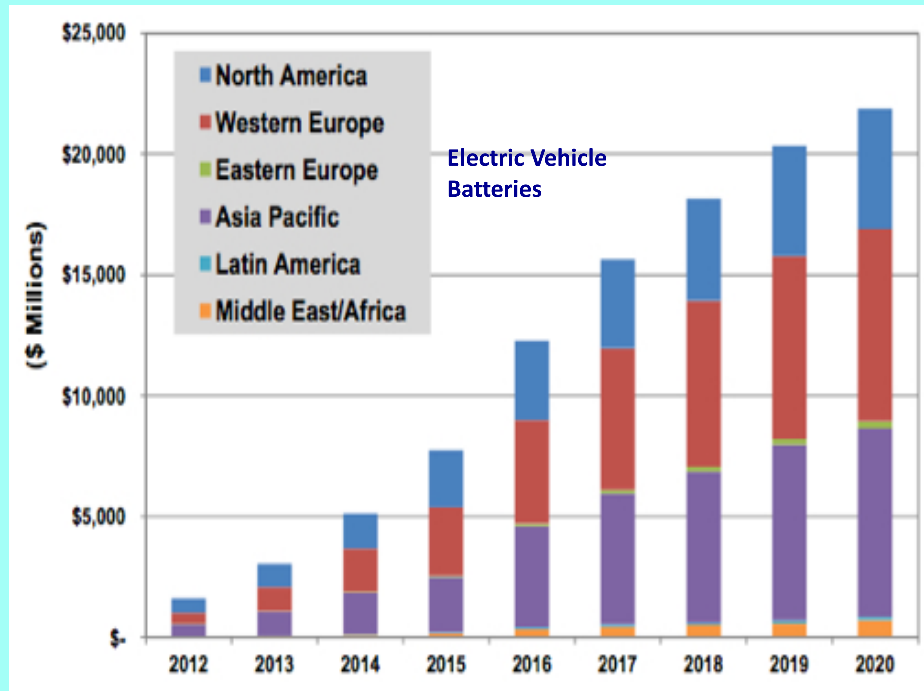


Not quite Moore's Law (computing power tends to approximately double every two years) but impressive growth nonetheless (energy density doubles each ten years).

The Dominance of Li-Ion Batteries in the Market

- Li-ion rapidly became the technology of choice especially for consumer electronics (3Cs-cell phones, computers and camcorders), electric vehicles, and also space missions
  - Higher specific energy and energy density
  - Longer storage life and cycle life
  - Lower maintenance due to low self discharge rate





Batteries in Electric Vehicles

Plug-in Hybrid

Battery System Level Goals	PHEV 40
Characteristic	
Available energy (kWh)	11.3
System weight (kg)	120
System volume (l)	80
Discharge power (kW, 10 sec)	50
Regen. power (kW, 10 sec)	25
Recharge rate (kW)	1.4-2.8
Cold cranking power @ -30C (2 secs) (kW)	7
Calendar life (years)	15
Cycle life (cycles)	5,000 deep discharge
Operating temp. range (°C)	-30 to +52

Cell Level Goals	PHEV40
Characteristic	
Specific energy (Wh/kg)	200
Energy density (Wh/l)	400
Specific discharge pulse power (W/kg)	800
Discharge pulse power density (W/l)	1,600
Recharge time (hours)	3-6
Specific regen. pulse power (W/kg)	430
Regen. pulse power density (W/l)	860
Calendar life (years)	15
Cycle life (cycles)	5,000
Operating temp. range (°C)	-30 to +52

Electric Vehicle

Energy Storage Goals	EV Battery	EV Cell
Characteristic		
Available energy (kWh)	45	NA
Discharge power density (W/l)	1,000	1,500
Specific discharge power (W/kg)	470	700
Specific regen. power at 20% DOD, 10 sec (W/kg)	200	300
Energy density @ C/3 discharge rate (Wh/l)	500	750
Specific energy @ C/3 discharge rate (Wh/kg)	235	350
Calendar life (years)	15	15
Cycle life to 80% DOD (cycles)	1,000, deep discharge	1,000, deep discharge
Operating temperature range (°C)	-30 to +52	-30 to +52
Selling price @ 100k units/year, $/kWh	125	100
Recharge time (hours)	<7, J1772	<7, J1772
Fast recharge time	80% ΔSOC in 15 minutes	80% ΔSOC in 15 minutes

Batteries for Present Battery Electric Vehicles sold in US.

Plug-in Hybrid

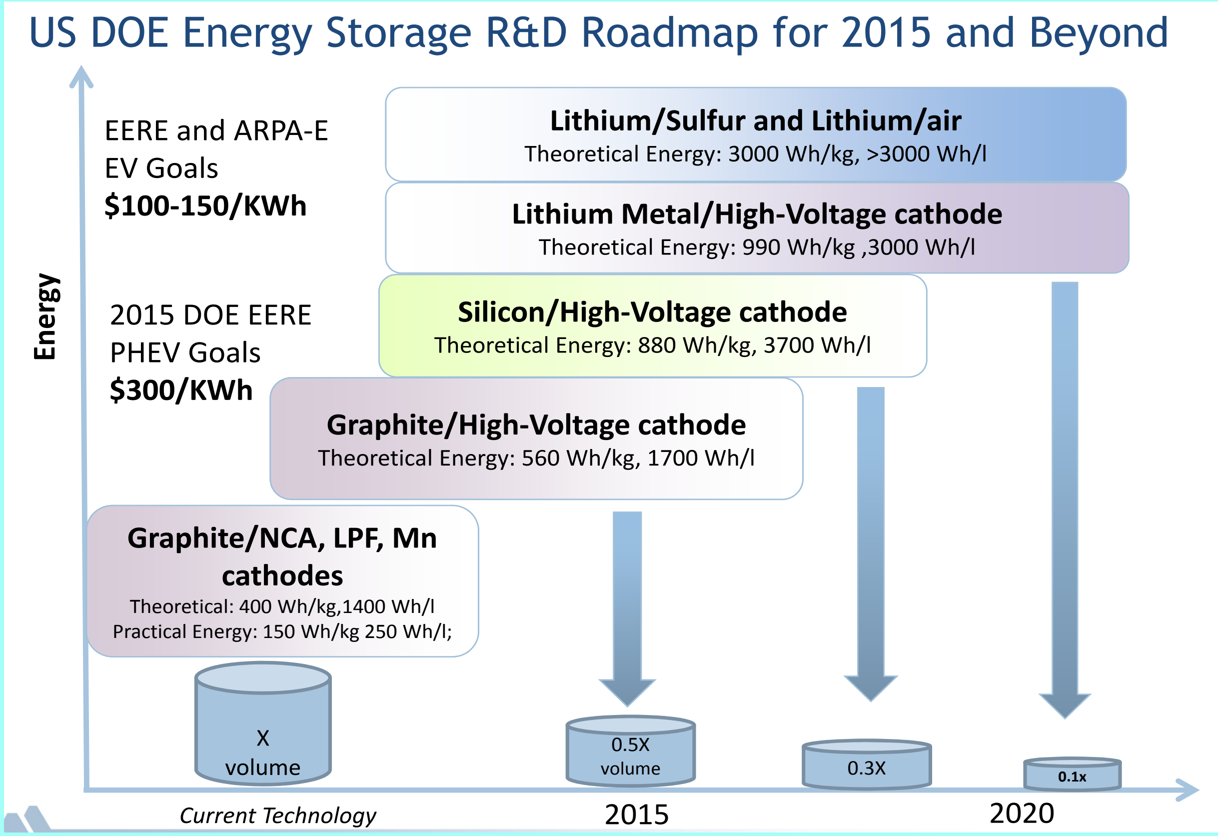
Manufacturer	Model	Battery Size (kWh)	Electric Range (mi)	Battery Chemistry	Battery Supplier
Chevrolet	Volt	18.4	53	C/NMC	LG Chem
Ford	Fusion Energi	7.6	21	C/NMC	Panasonic
Ford	C-Max Energi	7.6	21	C/NMC	Panasonic
BMW	X5	9.2	14	C/NMC	Samsung/Bosch
Hyundai	Sonata Plug In	9.8	27	C/NMC	LG Chem
Audi	A3 Plug In	8.8	16	C/NMC	Panasonic (Sanyo Div.)
Volvo	XC90 Plug In	9.2	25	C/NMC	LG Chem
BMW	i8	7.1	23	C/NMC	Samsung/Bosch
Porsche	Cayenne SE-Hybrid	10.8	14	C/NMC	Samsung/Bosch
BMW	3 Series Plug-in	7.6	14	C/NMC	Samsung/Bosch
Mercedes	S550 Plug In	6.4	20	C/NMC	Panasonic (Sanyo Div.)
Mercedes	GLE 550E Hybrid	8.8	19	C/NCA and C/NMC	Tesla and SK Innovation†
Porsche	Panamera SE-Hybrid	9.4	22	C/NMC	Samsung/Bosch
Cadillac	ELR	17.1	39	C/NMC	LG Chem

Electric Vehicle

Manufacturer	Model	Battery size (kWh)	Battery Chemistry	Battery Supplier	Vehicle range (mi)
Tesla	S	60–100	C/NCA	Panasonic/Tesla	208–315
Tesla	X	60–100	C/NCA	Pansonic/Tesla	208–315
BMW	i3	22,33	C/NMC	Samsung/Bosch	80,114
Nissan	Leaf	24,30	C/LMO (C/NMC)	AESC and LG Chem†	84,107
Volkswagen	e-Golf	24,35.8	C/NMC	Pansonic (Sanyo Div.)	83,124
Chevrolet	Spark	19	C/LFP	A123	82
Fiat	500e	24	C/NMC	Samsung/Bosch	87
Kia	Soul EV	27	C/NMC	SK Innovation	90
Smart	Fortwo EV	17.6	C/NMC	LG Chem	68
Ford	Focus EV	35.5	C/NMC	LG Chem	100
Mercedes	B-Class Electric	28	C/NCA, (C/NMC)	Panasonic/Tesla and SK Innovation†	85
Mitsubishi	I	16	LTO/LMO	Toshiba	62
Honda*	Fit EV	20	LTO/LMO	Toshiba	82
Toyota*	RAV4 EV	41.8	C/NCA?	Panasonic/Tesla	113

*Blomgren, Journal of The Electrochemical Society, **164** (1) A5019 (2017)*

Advanced Li-ion and Beyond Li-ion Technologies- DoE Roadmap



Cathodes: High voltage cathodes (recent focus Ni-rich NMC)

Anodes: Si anode and Li metal

Future systems: Li-S and Li-air

Li-ion Cells with Si anode

Technology Status

- Si anode and Metal oxide cathode
- Problem: Volume expansion of Si anode (400%)
- New Si anode designs to mitigation expansion
  - Nanocrystalline Si (with graphite)
  - Si Nanorods
- 300 cycles with 390 Wh/kg and in small pouch cells (<5 Ah)

Advantages:

- High specific energy of 400 Wh/kg

Mission Applications

- High energy- short life missions (small rovers)
- Aircraft, UAV, Drones, CubeSats

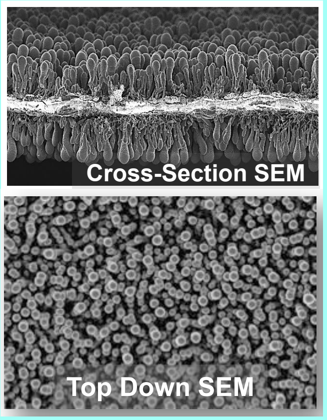
Technical Issues

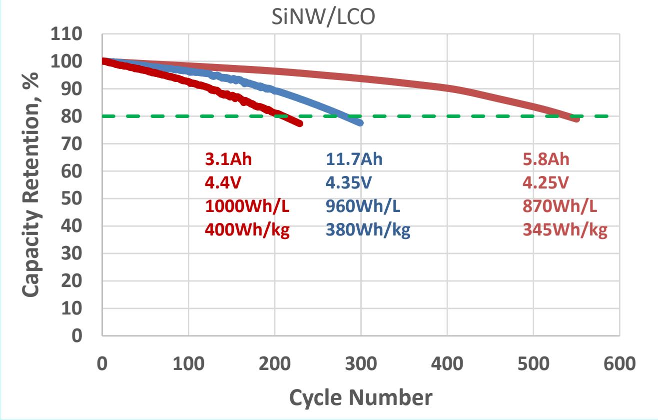
- Poor cycle life performance
- Questionable safety characteristics

Organizations

- Amprius, 3M, DoE

Si nanorods (Amprius)





Amprius Cell

Potential Capabilities

Cell Level	SOP Li-ion	Adv. Li Metal
Specific Energy (Wh/kg)	90-110	200-300
Energy Density (Wh/L)	150	350-450
Cycle Life (100% DOD)	~2,000	< 500
Calendar Life (Years)	5-10	< 5
Operating Temperature	-20 to +40°C	-30 to +30°C

Lithium Sulfur Rechargeable Batteries

Technology Status

- Li metal anode, S cathode in ether-based electrolytes.
- Problem: Polysulfides soluble in electrolyte
- New cathode designs to sequester sulfur products within the cathode
  - Carbon nanostructures as hosts
  - Metal sulfide blends (TiS_2, MOS_2) and ceramic –coated separators (JPL)
  - Protected Li anode (Ceramic electrolyte)
- 500 cycles with 300 Wh/kg and 100 cycles with 400 Wh/kg in small pouch cells (<10 Ah)

Advantages:

- High specific energy of 350-450 Wh/kg

Mission Applications

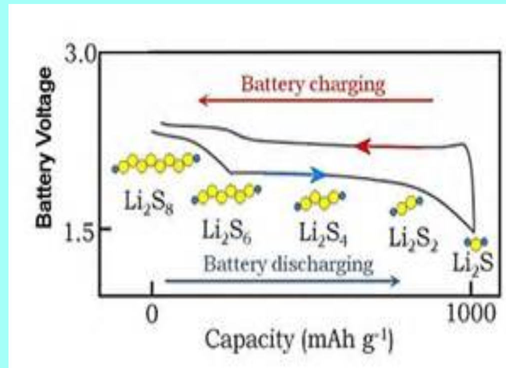
- High energy- short life missions (small rovers)
- Aircraft, UAV, Drones, CubeSats

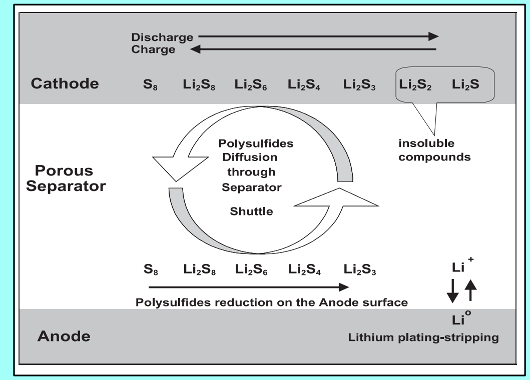
Technical Issues

- Poor high temperature performance
- Poor cycle life performance
- Questionable safety characteristics

Organizations

- Oxis Energy, Sion Power, Eagle Picher, DoE, JPL





Oxis Cells

Potential Capabilities

Battery Level	SOP Li-ion	Advanced Li-S
Specific Energy (Wh/kg)	90-110	250-300
Energy Density (Wh/L)	150	300-350
Cycle Life (100% DOD)	~ 2,000	100-500
Calendar Life (Years)	5-15	< 5
Operating Temperature	-20 to +30°C	-40 to +30°C

Lithium Metal Rechargeable Batteries

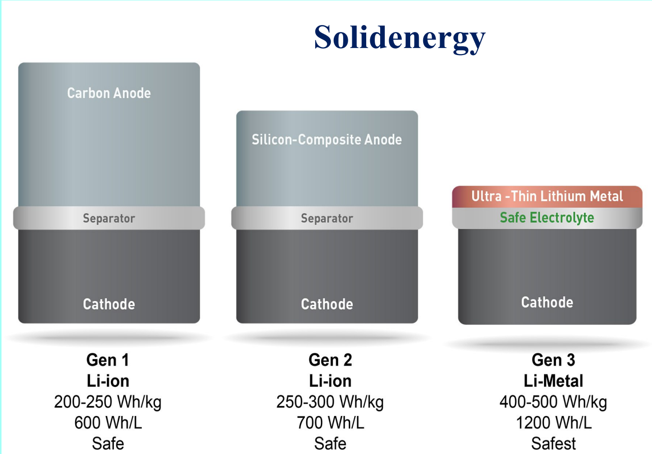
Technology Status
- Lithium metal replaces carbon anodes
- Challenge is to find a suitable electrolyte without Li dendrites
- TRL: Prototype cells (SEEO) with Solid Polymer (TRL 4) at 80°C
- Silicon alloy being viewed as a near-term alternate
- Liquid electrolytes (TRL 2 with <100 cycles)

Advantages:
- High specific energy and energy density
- Long cycle life
- Good low temperature performance

Mission Applications
- High energy- short life missions (small rovers)

Technical Issues
- Poor high temperature performance
- Poor cycle life performance
- Questionable safety characteristics

Active Players
- SEEO, DoE (JCESR), Solid Energy, Universities, Hydro-quebec



Potential Capabilities (Cell Level)

Cell Level	SOP Li-ion	Adv. Li Metal
Specific Energy (Wh/kg)	90-110	250-350
Energy Density (Wh/L)	150	300-400
Cycle Life (100% DOD)	~2,000	< 500
Calendar Life (Years)	5-10	< 5
Operating Temperature	-20 to +40°C	-30 to +30°C

Solid State Rechargeable Batteries

Technology Status

- New Solid electrolytes being developed
  - Garnet Oxides.
  - LATP (Lithium Aluminum Titanium Phosphate
  - LIPON
- Coin cells & Small format laboratory cells

Advantages:

- Improved safety (no runaway),
- Long cycle life and calendar life
- Good high temperature resilience,
- heat-sterilizable

Mission Applications

- Low-power applications (sensors),
- Long-life (calendar life and cycle life)
- Personal electronic devices

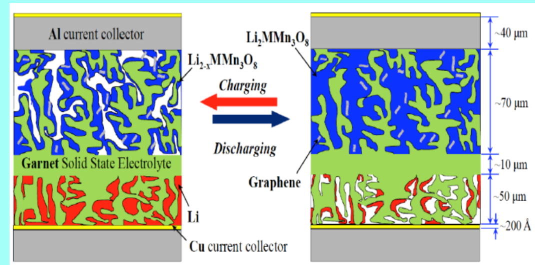
Technical Issues

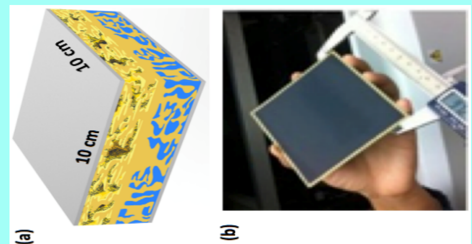
- Poor rate capability
- Difficult to scale up to high capacity cells
- Poor low temperature performance

Active Players

- Front Edge, Univ. of Maryland, Solid Power,

Univ. Maryland

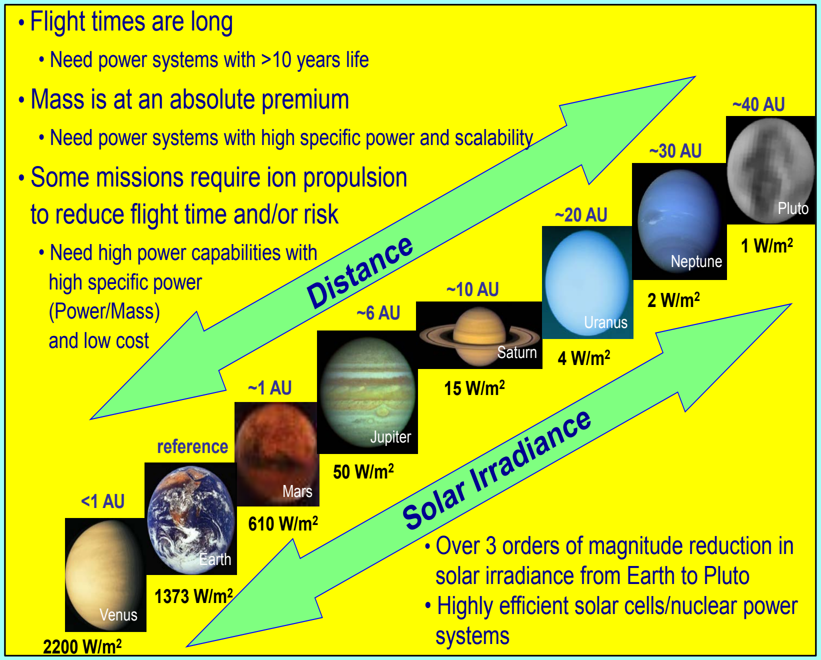


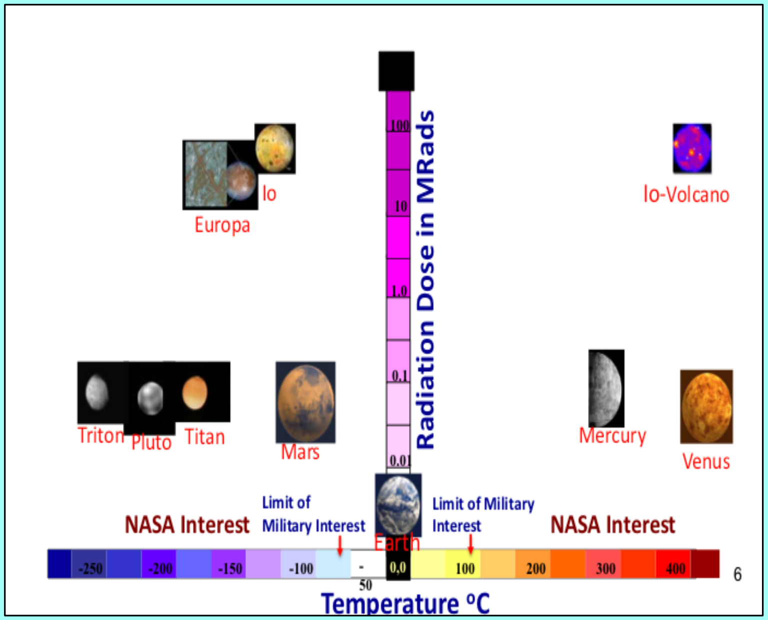


Potential Capabilities

Cell Level	SOP Li-ion	Adv. Solid State
Specific Energy (Wh/kg)	90-110	250-350
Energy Density (Wh/L)	150	300-400
Cycle Life (100% DOD)	~2,000	>10,000
Calendar Life (Years)	5-10	>20
Operating Temperature	**-20 to +30°C**	**10 to +80°C**

Environmental challenges for Power Systems in Solar Missions





- Low solar irradiance at Jupiter and beyond.
- Most deep space mission concepts to Jupiter and beyond would use radioisotope power systems (Radioisotope thermoelectric generator or RTG)

- Challenging environments (temperature and radiation)

Why do we need batteries

- Energy storage devices used in robotic planetary science missions include primary (non-rechargeable) batteries, secondary (rechargeable) batteries, and capacitors. Fuel cells have been used in human space missions but not in planetary science missions.
- Rechargeable batteries are used to:
  - Power to the spacecraft during launch before deployment of the solar panels.
  - Power during cruise anomalies (Trajectory Control Maneuvers).
  - Power to the spacecraft, its equipment, and instrumentation during Sun eclipse periods.
  - For Load leveling in radioisotope powered missions during peak power operations such as telecoms, sample drilling and surface mobility.
  - Missions include used in planetary orbiters (Mars Global Surveyor, and Mars Reconnaissance Observer), Mars landers (Mars Pathfinder, Phoenix Lander), and Mars rovers (Spirit, Opportunity, and Curiosity)
- Primary batteries are used in:
  - Missions that require a single use of electrical power for a period of a few minutes to several hours.
  - Mission where a rechargeable battery is not desirable or no energy source is available for recharging
  - Such missions include planetary probes (Galileo, Deep Impact, and Huygens), sample return capsules (Stardust and Genesis), Mars Landers (MER), and Mars Rovers (Sojourner)
- Capacitors are used in
  - Applications requiring repeated high power and short duration pulses (seconds).
  - The Galileo and Cassini missions used capacitors for firing pyros and stepping motorized instrument platforms.

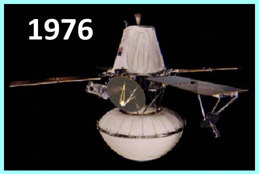
Battery Needs of Space Missions

Space Exploration	Mission	Technology Drivers	Relevant Technology
Earth	Geosynchronous Earth Orbit Satellite	Long Life (1000 deep discharge cycles) and Long Calendar life (10 years)	Rechargeable Battery; Mostly Nickel-Hydrogen, Being replaced by Li-ion batteries
	Low Earth orbit (LEO) Satellite	Long Cycle Life (60,000 cycles @ 40% DOD) and Long Calendar life (5-10 years)	
	ISS		
Planetary mission	Surface Missions (Landers and Rovers)	High Wh/Kg and Wh/l; Wide temperature performance	Ag-Zn (in 1996) and currently Li-ion
	Orbiters	Long Cycle Life (60,000 cycles @ 40% DOD); Long Calendar life (5-10 years)	Rechargeable Battery; Mostly Nickel-Hydrogen, Being replaced by Li-ion batteries
	Micro-probes	Low temperature performance; Impact tolerance, Compact and Lightweight;	Lithium Primary Battery
Comet/Asteroids	Sample Return	Long Shelf life and High Wh/Kg, Wh/l	Lithium Primary Battery
Jovian Planets	Orbiters and Landers	High radiation tolerance and Long Calendar life (> 6 years)	Previously Capacitors, Being replaced by Lithium-Ion
Outer Planets (Pluto)	Fly-by	High radiation tolerance and Long Calendar life (> 6 years)	Lithium-Ion

- High gravimetric and volumetric energy densities are always important to reduce the launch costs and increase the science payload.

Mars Orbital Missions

- **Support four science themes of the Mars Exploration Program:**
  - **Climate, geology, life, and preparation for human exploration.**
- **Identify scientifically interesting landing sites for further study**
  Assist in Communications and Navigation
  - **A key role as communications relays for rovers, landers and probes**
  - **Assist with navigation of other spacecraft approaching Mars.**

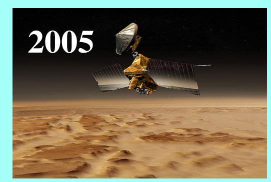


Viking
Operated for 2-4 years
Ni-Cd batteries
Four 8 Ah, 28V

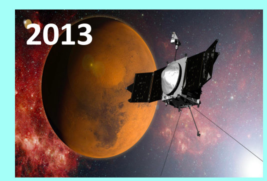
Mars Global Surveyor
Operated for ~ 9 years
Ni-H_2 batteries
20 Ah, 2-CPV 8S2P

Mars Odyssey
Operating since 2002
Ni-H_2 batteries
16 Ah, 2-CPV 11S1P
Will support Mars 2020

Mars Express
Operating since 2004
Li-Ion batteries
67.5 16 Ah,



Mars Reconnaissance Orbiter (MRO)
Operating since 2006
Ni-H_2 batteries
50 Ah 2-CPV, 2P11S
(Will support Mars 2020)



MAVEN
(Mars Atmosphere and Volatile Evolution)
Operating since 2013
28V,110Ah Li-Ion

- Until recently, the long-life missions used Nickel hydrogen batteries, because of long cycle life and calendar life.
- Other examples Stardust, Genesis, Dawn, OCO and all satellites.
- Outer planetary missions were powered by RTG, e.g., Galileo, Cassini. Capacitors were used instead of batteries

RTG Only (570W)

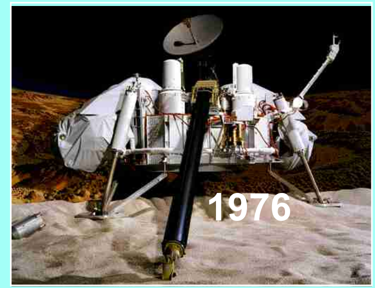
Li-ion batteries have started being used in long-life missions

Mars Surface Missions (Through 90s)

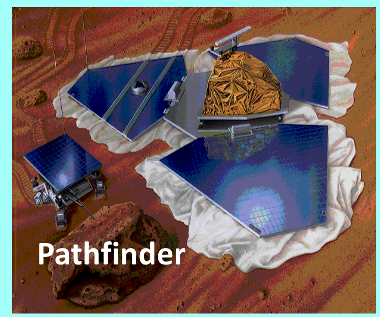
- The first Mars Lander, Viking Landers (I and II), had an RTG and Ni-Cd batteries for peak power.
- Mars Pathfinder and Sojourner (Lander and Rover) 1996
- Lander had Silver-Zinc Battery: 27 V and 40 Ah (actual 55Ah) from BST
  - Battery Challenges: i) Inverted orientation during ATLO/ launch, ii) Fourteen month total wet stand including cruise, and 40 operational cycles without electrolyte leakage.
  - Supported through 84 Sol 84, albeit at reduced loads (goal : 30 sols).
- Sojourner rover had a primary battery ($Li\text{-}SOCl_2$) with a solar array supported 84 days (goal: 4 sols)

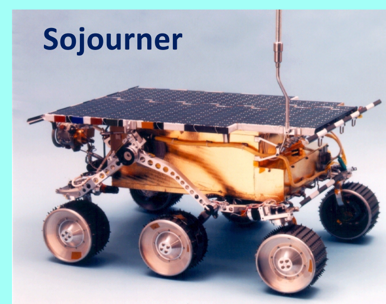
A battery with high specific energy and long life was sadly missing!

Viking Lander



1996 (Lander and Rover)





Mars Surveyor Program (MSP01) Lander (2001)

- NASA - DoD consortium set up in 1995 to develop large-format Li-ion cells within US.
  - Technology developed together with NASA Laboratories (JPL and GRC) and Industry (Yardney and SAFT)
- Li-ion cells of 5-55 Ah, 120 Wh/kg and long-life and with improved low temperature performance
- Batteries were built and successfully qualified. Mission was, however, cancelled.
  - Would have been the first planetary mission to utilize lithium-ion battery.
- Resurrected later as Phoenix lander mission (2007)
- Two parallel batteries each with eight 31 Ah Li-ion cells (8S2P)
- Helped in generating valuable data to validate the technology for future missions (Mars Exploration Rover)

Chemistry

- **MCMB anode and $LiNi_{0.8}Co_{0.2}O_2$ cathode**
- **JPL's Gen1 low temperature electrolyte**
- **Flat Plate Prismatic Custom cell**

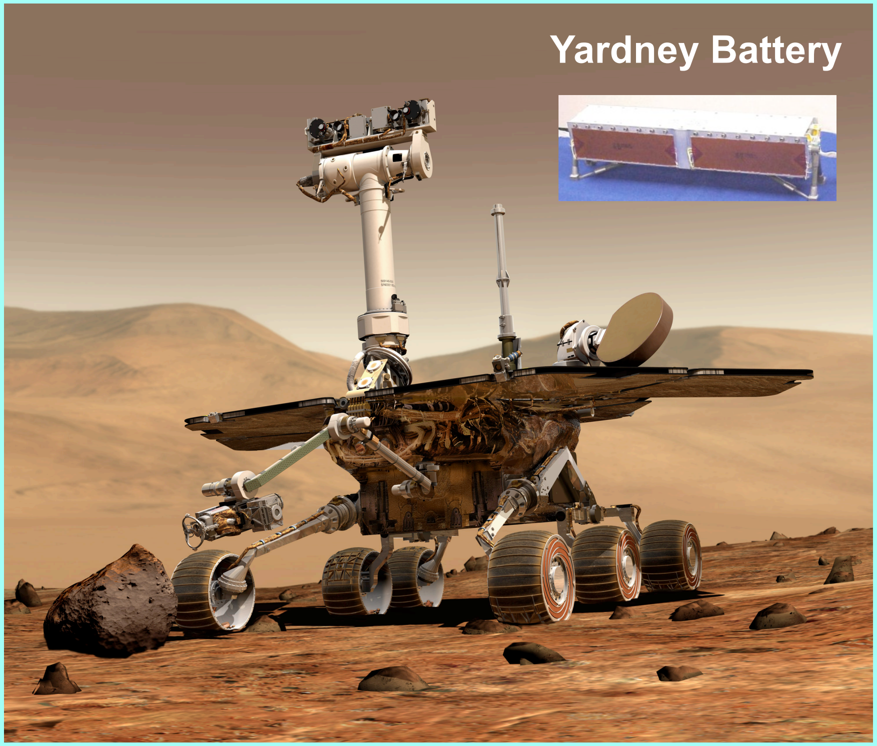
•Battery: 32 V: 62 Ah

•Specific energy : 104 Wh/kg

•Temperature:-20 to 40^oC

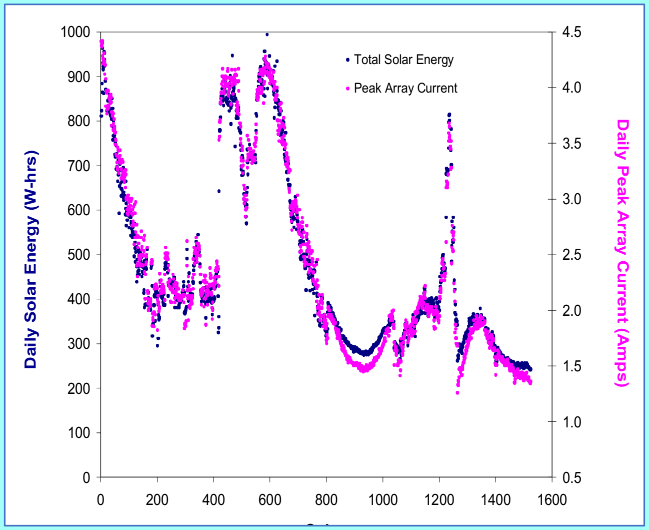
Mars Exploration Rover- Spirit and Opportunity (2003)

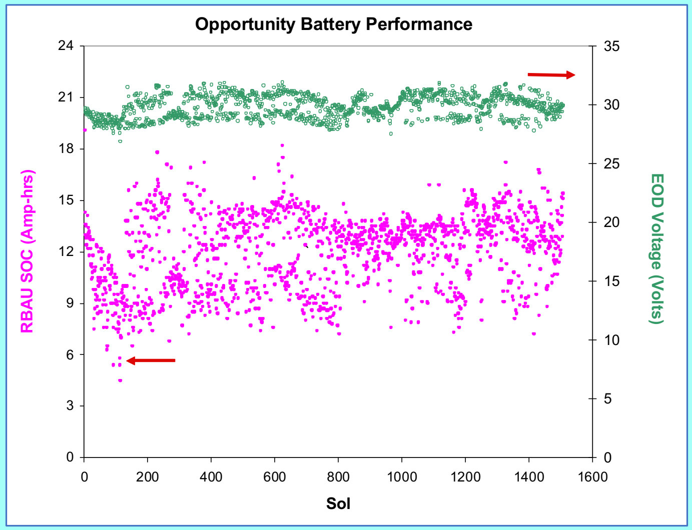
- First major NASA mission with Li-ion batteries
- Two six-wheeled, solar-powered robots standing 1.5 m high, 2.3 m wide and 1.6 m long and weighing 180 kg
- Energy Source: Triple-junction solar array with a BOL energy of 1000 Wh/sol
- Excellent performance from the Li-ion Battery, both in cycle life and Calendar life (against 90 days of design life) with astounding scientific findings.
  - Spirit Operated over 9 years
  - **Opportunity rover is still operational with over 5000 Martian sols and 10 km**
- Mission enabling: Alternate battery technologies were not viable.
  - Ag-Zn battery would have limited the life to six months or less and a $Ni\text{-}H_2$ battery would be about four times heavier (7.5 kg vs 28 kg)
- Cell balancing methods utilized to prevent overcharge.
- Led to the use of Li-ion batteries on several missions not only within JPL but across NASA (e.g., GSFC missions).

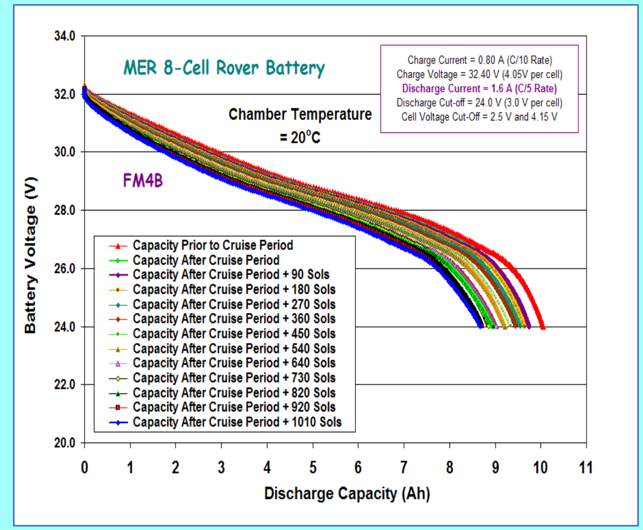


- Chemistry Same as MSP 01 with NCO Cathode, MCMB anode and JPL 1st Generation low temperature electrolyte
  - Cell: Custom 10 Ah; Battery: 32 V, 20 Ah; Specific energy : 90 Wh/kg
  - Temperature:-20 to 30°

Mars Exploration Rover- Spirit and Opportunity (2003)



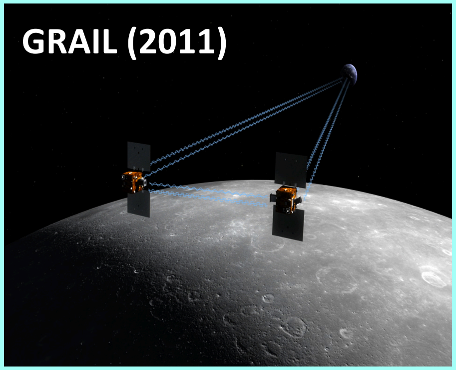


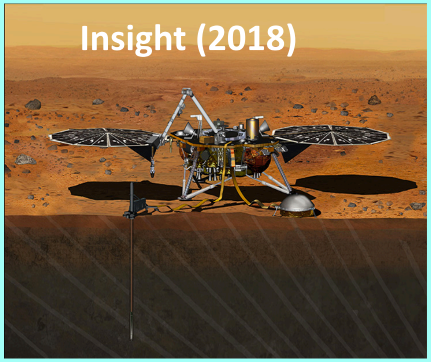


- Impressive performance of Li-ion batteries (30 V, 20 Ah) on the Mars Exploration rovers, demonstrating great resilience and longevity
  - Spirit survived through 1000 sols
  - Stable voltages on spacecraft (45% Depth of discharge)
  - 70% capacity retention in laboratory tests.

- **Opportunity still operating (14 years, 5000 sol, >10 km)**

Missions Using Based on Large Prismatic cells





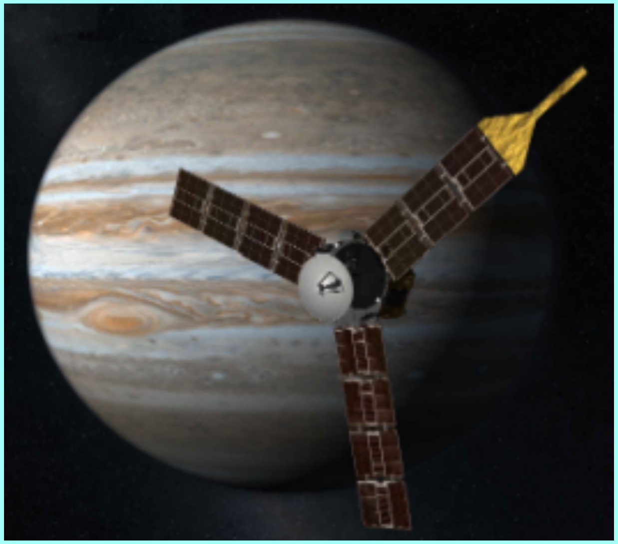
- Custom prismatic cells from 10-50 Ah from Yardney
- Chemistry (MCMB (graphite) anode, NCO (or NCA) cathode and low temperature electrolyte

Mission to Jupiter (JUNO) (2011)

- First solar powered S/C to Jupiter.
- Launched in August 2012, Juno is in orbit and studying the planet's composition, gravity field, magnetic field, and polar magnetosphere.
- Entered Jupiter orbit July 2016, and with its infrared and microwave instruments will measure the thermal radiation emanating from deep within Jupiter's atmosphere to assess the abundance and distribution of water, and oxygen.

Battery Challenges

- Required batteries with long calendar life (over six years) and radiation tolerance.

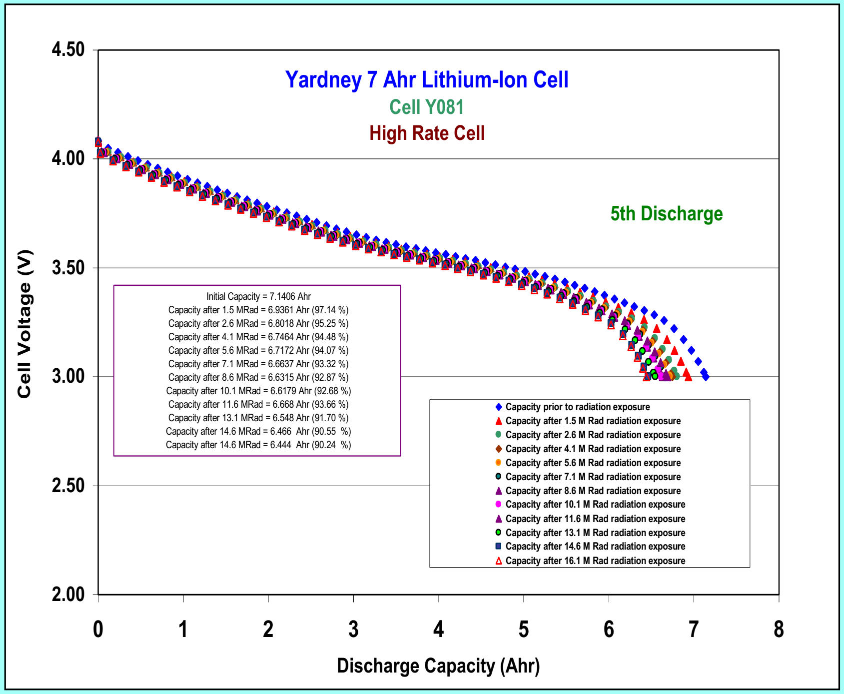


Li-Ion Battery

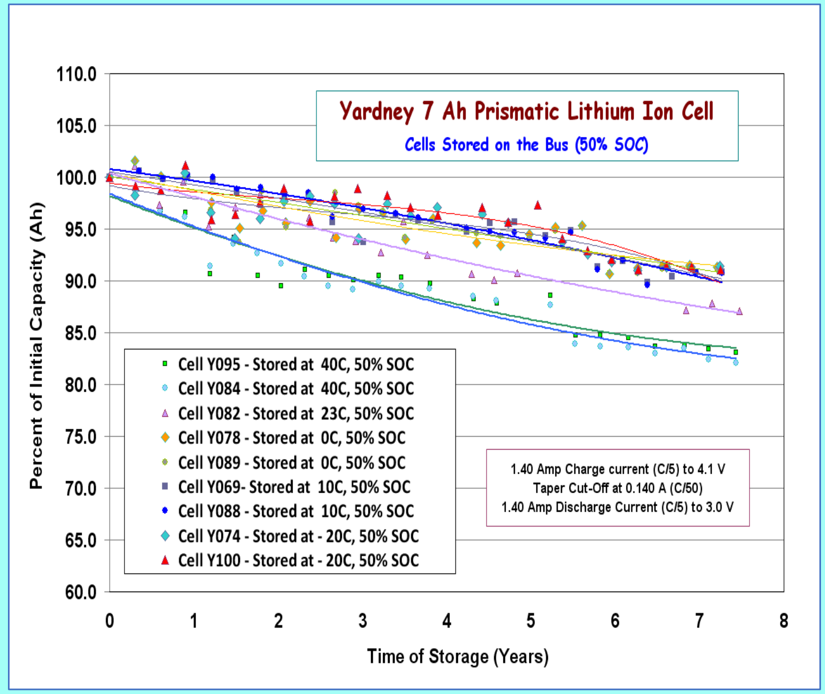
- **Chemistry (Same as MER)**
- **Cell: Custom 55 Ah**
- **Battery: 32 V, 110 Ah**
- **Specific energy : 105 Wh/kg**
- **Temperature:-20 to 30^{o}C**

Validation of Li-ion Batteries for Juno

Radiation Tolerance of Li-Ion Cells



Storage of Li-Ion Cells



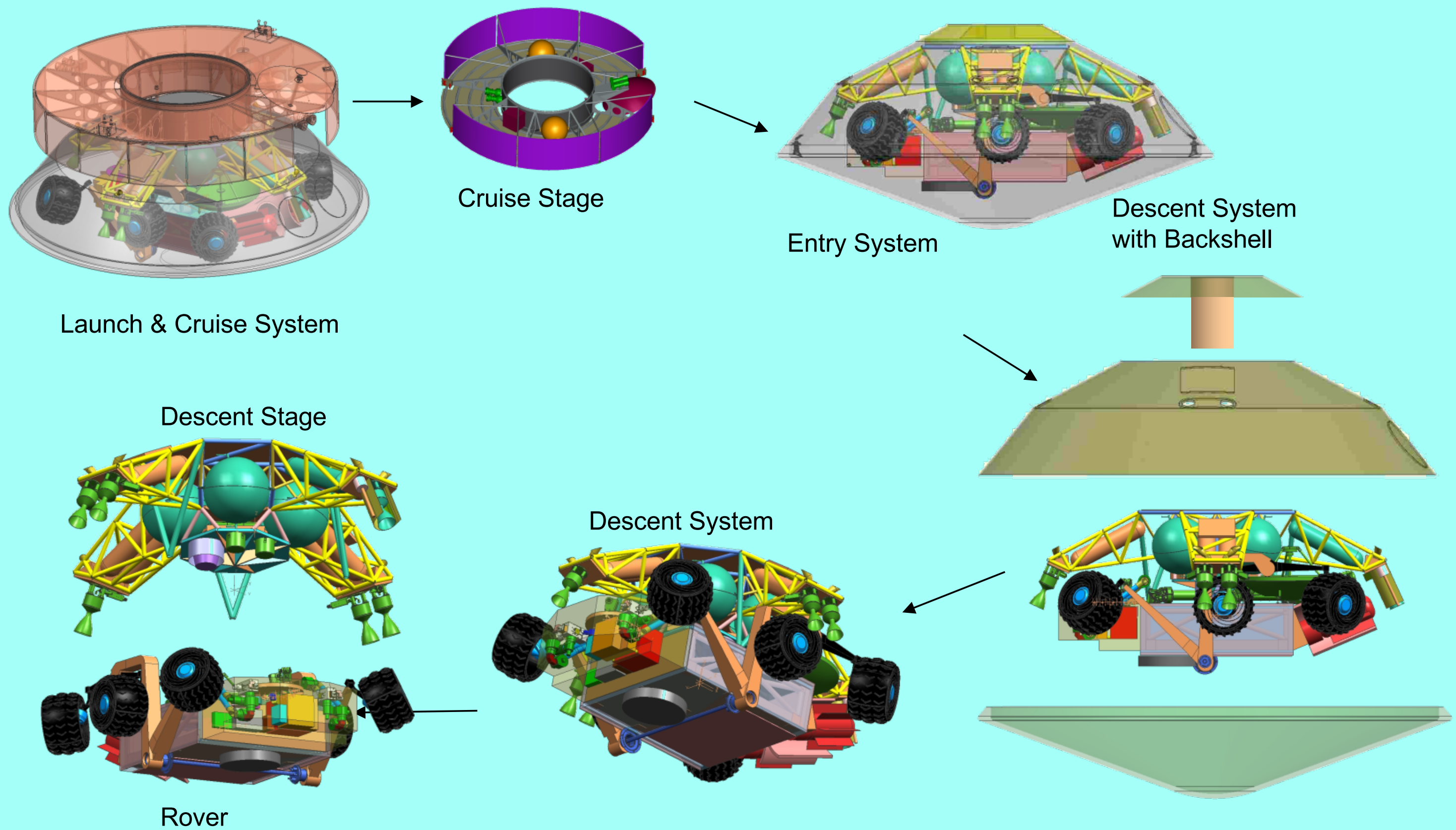
- Demonstrated tolerance of Li-on cells to high-intensity radiation environments (Cobalt-60). Cells retained >95% capacity after exposure to 18 Mrad.
- Calendar Life demonstrated through real-time testing

Mars Science Laboratory (MSL) Curiosity Rover

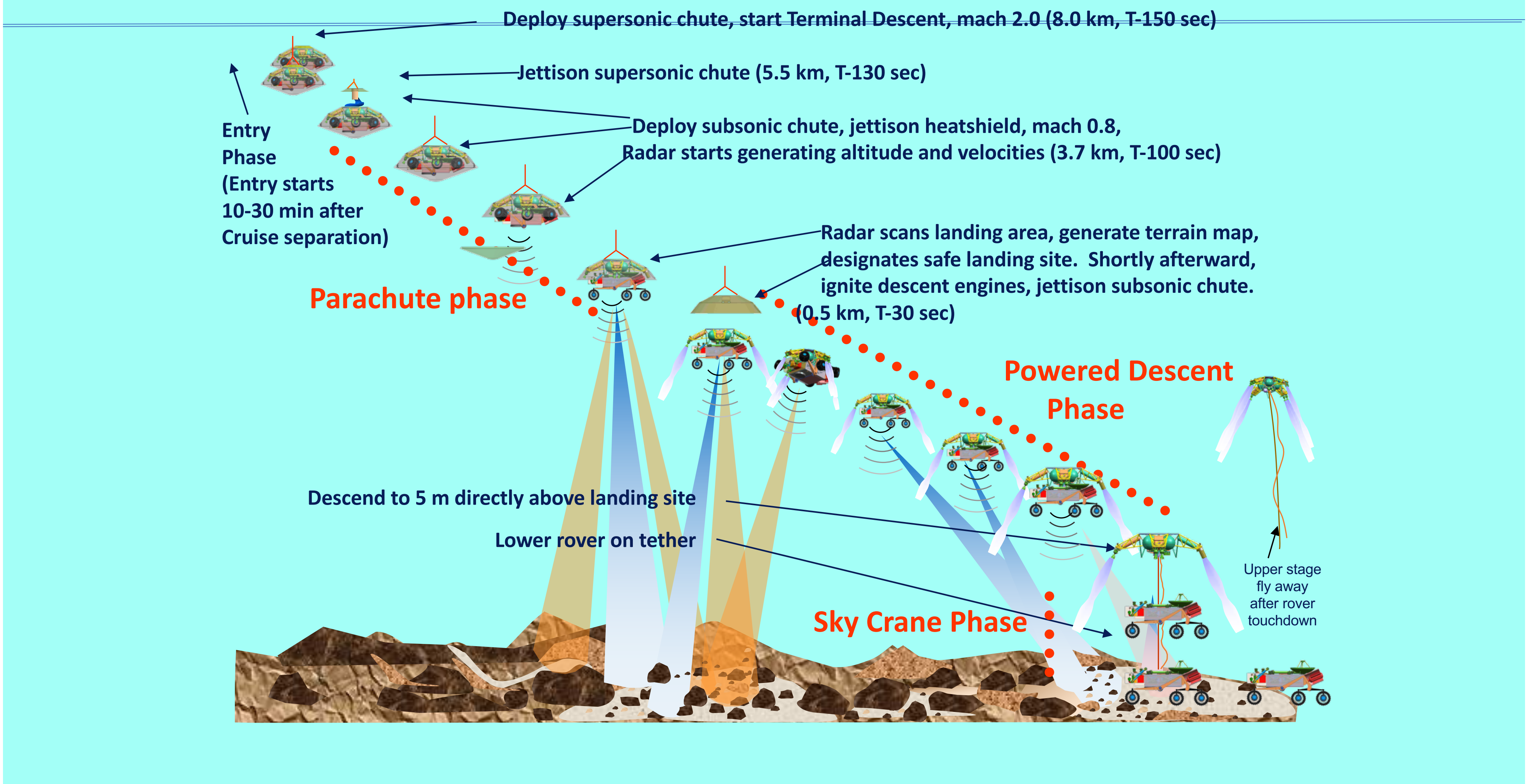
- **Science Goals**: To assess habitability: whether Mars ever was an environment able to support microbial life.
  - The biggest, most advanced suite of instruments ever sent to the Martian surface.
  - Analyze dozens of samples scooped from the soil and cored from rocks in the onboard laboratory to detect chemical building blocks of life (e.g., forms of carbon) on Mars.
- Landing: Parachute assisted and powered descent, lowered on tether like sky crane.
- **Programmatic Goals** : To demonstrate the:
  - Ability to land a very large, heavy rover to the surface of Mars
  - Ability to land more precisely in a 20-kilometer (12.4-mile) landing circle
  - long-range mobility (5-20 kilometers or about 3 to 12 miles)
- **Highlights:**
  - **Curiosity has operated over 1500 Sols to-date**
  - After 2 years and almost 9 km of driving, Curiosity has reached the base of Mount Sharp
  - During the first year, the rover fulfilled its major science goal of determining whether Mars ever offered conditions favorable for microbial life.
  - **As of Sol 1507, Curiosity has driven 9.16 miles (or 14.75 kilometers)**

- Two 8-cell batteries in parallel (8s2p).
- 24-32.8 V, 86 Ah (MER, Grail, Juno Chemistry)
- Qualification Temperature range: -30^{o} to +40^{o}C.
- Operating Temperature Range: -20^{o} to +30^{o}C
- **Required Life: ~ 4 years**
- **Surface Life: 670 Sols of operation.**
- Battery temperature controlled with a combination of heaters and radiators

MSL Major Spacecraft Assemblies

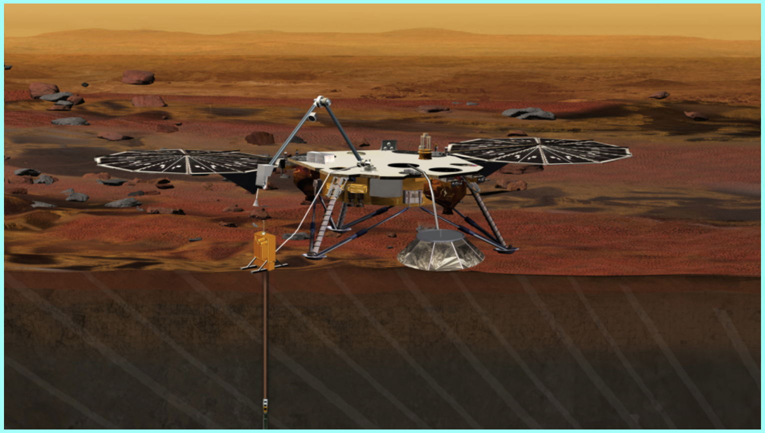


MSL Entry, Descent, and Landing Timeline



NASA's Mars InSight Lander

- InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) is a NASA Discovery Program mission that will place a single geophysical lander on Mars to study its deep interior.
- Mission will consist of a spacecraft built by Lockheed Martin Space Systems Company based on a design that was successfully used for NASA's Phoenix Mars lander mission
- Science Goals:.
  - InSight is a terrestrial planet explorer that will address the processes that shaped the rocky planets of the inner solar system (including Earth) more than four billion years ago
  - InSight will probe beneath the surface of Mars, detecting the fingerprints of the processes of terrestrial planet formation
- In January 2016, the March 2016 launch date of InSight mission was suspended to allow the repair of a leak in a section of the prime instrument in the science payload.



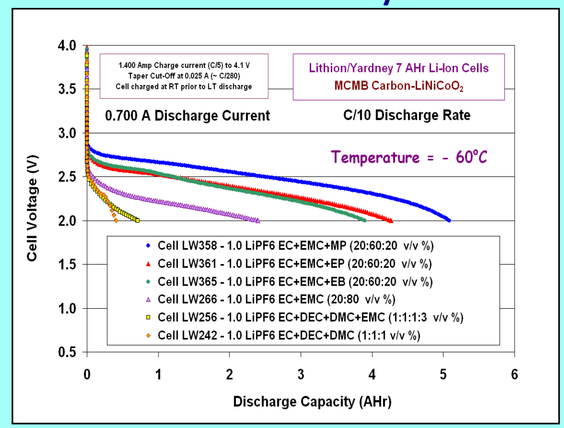
Battery Details

- Two 8-cell batteries (connected in parallel)
- Manufactured by Eagle-Picher Technologies / Yardney Division
- 24-32.8 V (Phoenix Battery Design)
- Qualification Temperature range: - 40°C to +50°C.
- **Operating Temperature Range: -30° to +35°C**
- **Required Life: ~ 4 years**
- **Surface Life: 709 Sols of operation.**

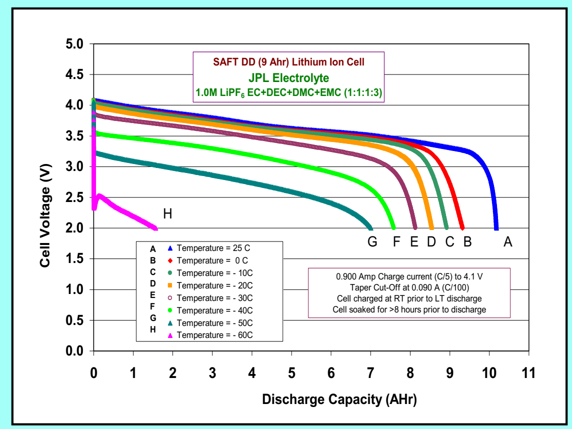
Low Temperature Electrolytes in Li-ion Cells

- Wide Operating Temperature Electrolytes (NASA Supported)
  - Planetary Rovers and Landers Applications
  - Early Generation Ternary Electrolyte (-20 to +40°C)
  - Quaternary Carbonate-Based Electrolytes (-40 to +40°C)
  - Use of Ester-Based Co-Solvents (-60 to +40°C)
  - Use of Electrolyte Additives with Ester-Based Electrolytes
- Electrolytes with Improved Safety Characteristics (NASA)
  - Use of Flame Retardant Additives
  - Use of Fluorinated Esters and Carbonates
  - High Voltage Electrolyte Systems
- Electrolytes for Automotive Applications (DOE Supported)
  - Wide Operating Temperature Electrolytes (-30 to +60°C)
  - High Voltage Electrolyte Systems
- Electrolyte Screening Techniques

Ester Blends-Yardney Cells



Low-EC All Carbonate -SAFT Cells

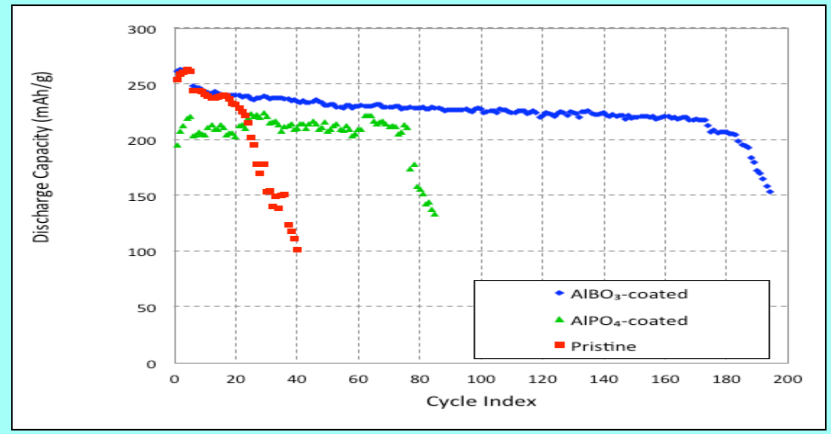


- At a moderate discharge rate at –60°C (C/10), the methyl propionate-based electrolyte was observed to deliver ~ 52 Wh/Kg, vs. only ~4 Wh/kg for the ternary blend.

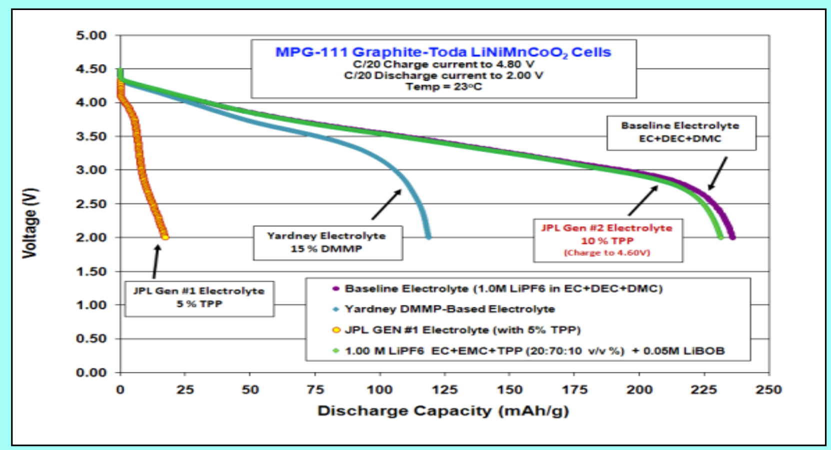
Advanced Space Power Systems- Li-ion Batteries

- High specific energy 400 Wh/kg cells for Extra-Vehicular Activities (EVA)
- Lithium- excess Layered-Layered composites of Li_2MnO_3 and $Li(Mn,Ni,Co)O_2$
  - High capacity > 250 mAh/g with optimized composition.
  - Developed a new surface coating ($AlBO_3$), which improves the performance of high voltage cathodes.
- Developed new electrolytes with reduced flammability (and thus enhanced safety) and high voltage compatibility for Li-ion cells.
  - Flame retardant additive (triphenyl phosphate – 5-15%) with ‘no loss’ in performance.
  - amounts of flame retardant additive (triphenyl phosphate – 5-15%) with ‘no loss’ in performance.

High capacity/voltage cathodes with new coating ($AlBO_3$)

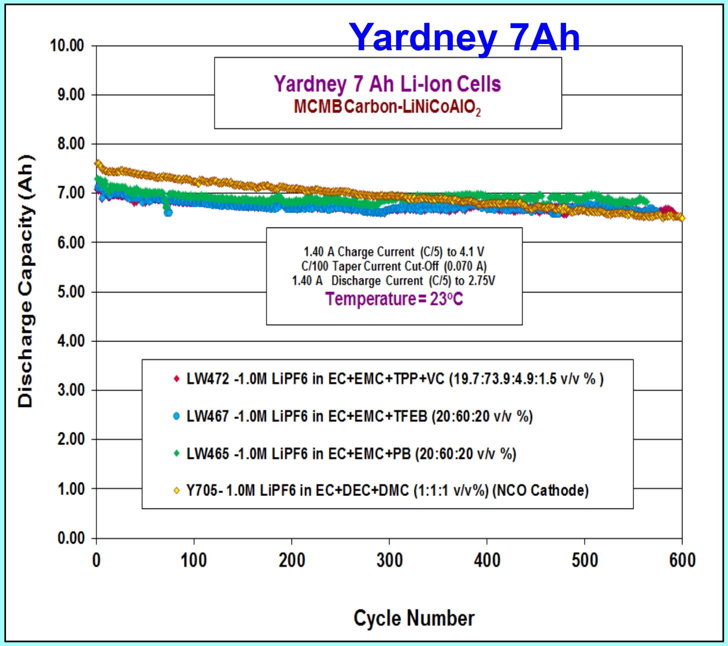


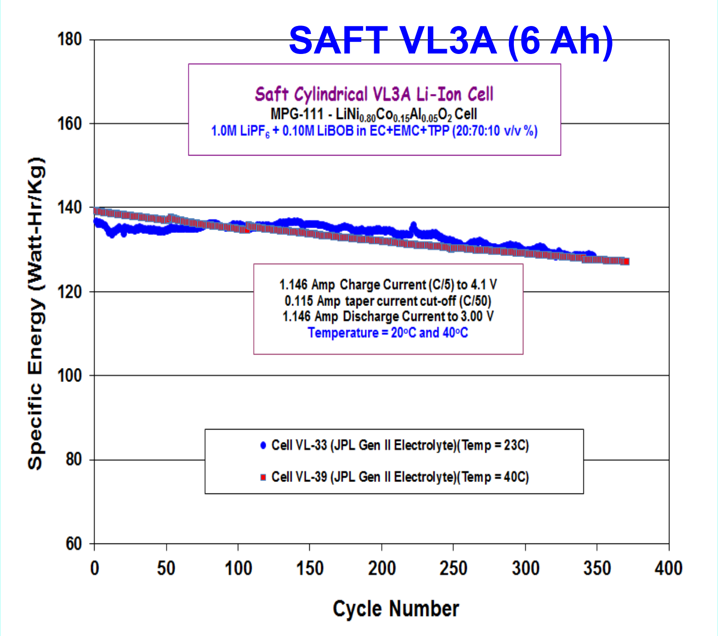
Low-flammability Electrolytes



Low Flammability Electrolytes for the SOA Li-Ion Cells

- Demonstrated excellent cycle life and rate capability of low flammability electrolytes in prototype cells for various aerospace Li-ion chemistries
  - Yardney Cells with MCMB anode and $LiNi_{0.8}Co_{0.2}O_2$ cathode
  - SAFT chemistry with MPG111 graphite anode and $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ cathode



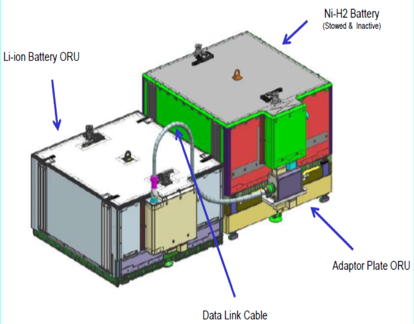


- *Low Flammability electrolytes do not compromise the performance of Li-ion cells*

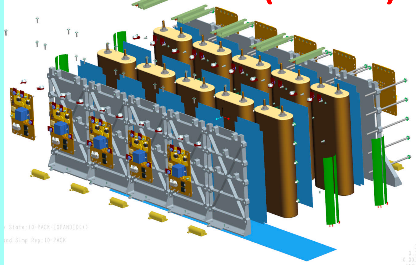
Li-Ion Batteries on International Space Station

Cell Characteristics	ISS NiH2	ISS Li ion
Rated capacity	81 Ah	134 Ah
Energy density	~65 wh/kg	~150 wh/kg
Discharge voltage	1.25 V	> 3.6 V
Self discharge rate	~7% per day (20°C)	< 0.05% per day
Cycle life in LEO (20%-30%DOD)*	*~ 10 years (60,000-75,000 cycles) @ 20%-30% DOD*	*~ 10 years (58,000 cycles) @ 20%-25%DOD*
Spec Cycle life	6.5 years @ 35%	10 years @ ISS power levels
Storage life	4 years	6 years
Overcharge	Tolerant	Controlled by 2 FT design
Total Energy Storage (Important for contingency operations)	8 kW-hr (Two ORUs combined)	15 kW-hr (One ORU)
Battery Weight	744 lbs (Two ORUs)	415 lbs (One ORU)

- Reduced Mass and Volume -
- Replacement of two NiH_2 ORUs with one Li-ion ORU and adapter plate
- More power available
- Half the logistics flights and lower costs
- Fewer EVAs to replace batteries



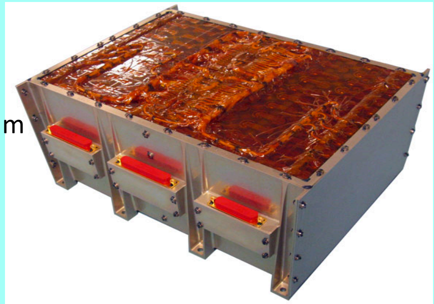
GS Yuasa Cells (135 Ah)



Adaptation of Commercial Li-Ion Cells for Space Missions

Flight Batteries using commercial 18650 cells (ABSL)

- Sony Hard Carbon – Lithium Cobalt Oxide
- Built-in protection devices: PTC (thermal fuse) CID (Current Interrupt device), vent
- Consistent cell fabrication by Sony
- Further, the cells are well matched using proprietary methods by ABSL
- *No need for cell balancing electronics based on the cell uniformity*
- Redundancy from multiple parallel strings.
- Several new high energy cells available

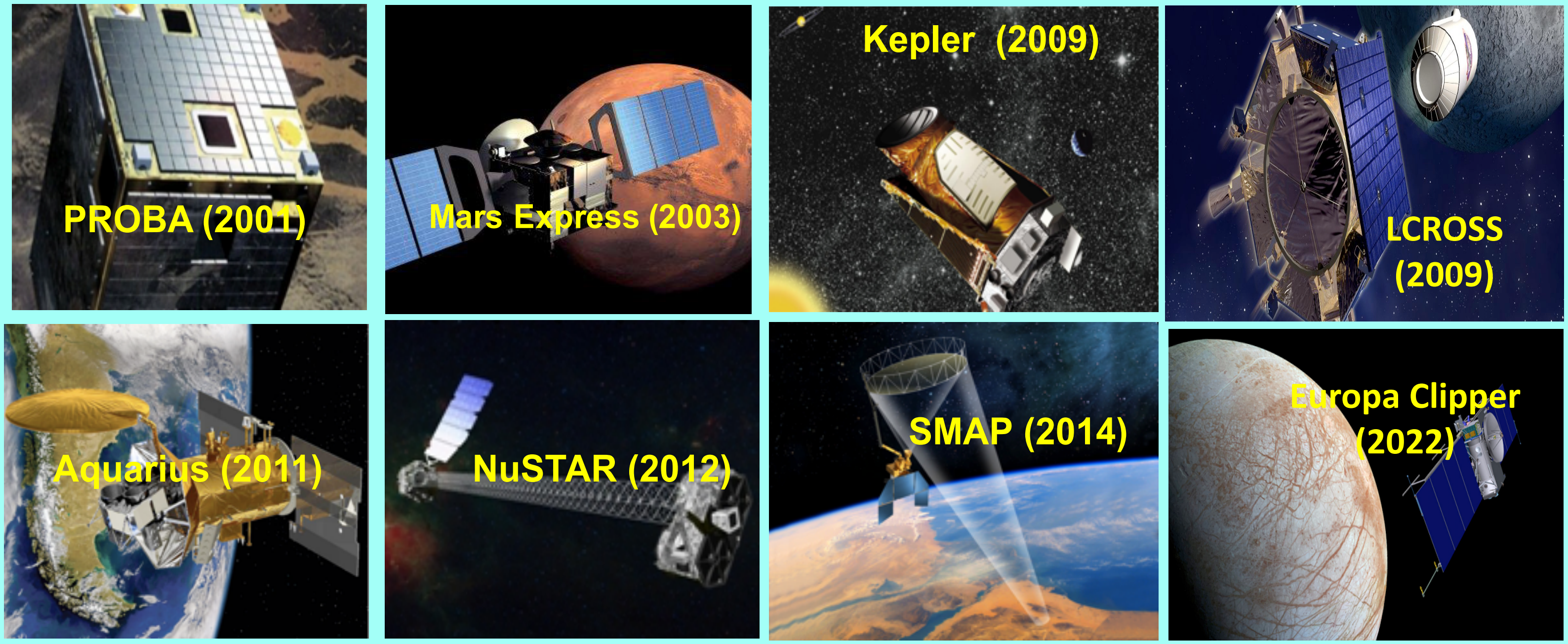


Several Battery Deigns Available (ABSL) (8S10P, 8S16P, 8S52P)

C/10 at RT	Panasonic NCR GA	Samsung 3.5E	Sony VC7	LG MJ1
Discharge Capacity (Ah)	3.34	3.49	3.5	3.41
Discharge Energy (Wh)	12.16	12.7	12.72	12.46
DC Internal Resistance (mohm)	38	35	31	33
Average Mass (g)	47	46	47.4	46.9
Average Volume (L)	0.0173	0.0173	0.0173	0.0173
Specific Energy (Wh/kg)	259	276	269	266
Energy Density (Wh/L)	704	733	735	720

Analogy with TESLA battery using Panasonic cells

LI-Ion Batteries with COTS cells for Space Missions



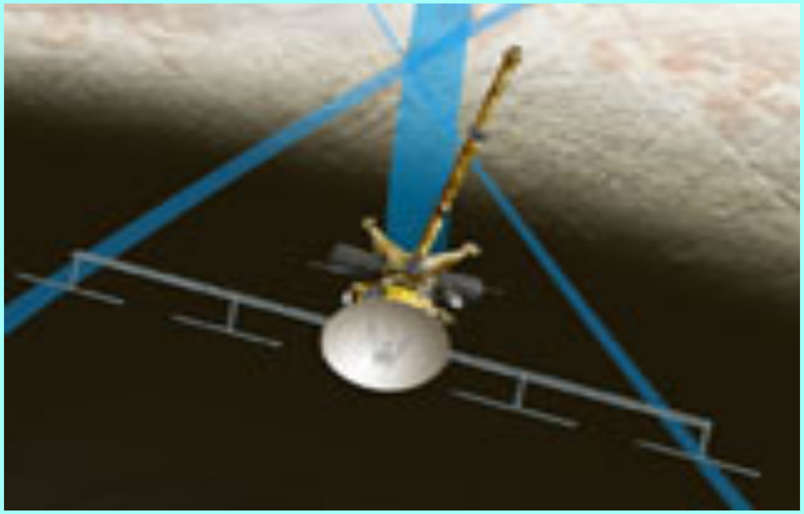
- All these missions used batteries using Sony HC 18650 cells (hard carbon–$LiCoO_2$) (110 Wh/kg)
- For the upcoming Europa Clipper, we are planning to use E-One Moli M cells (220 Wh/kg)
- No need for cell balancing electronics

Europa Clipper Mission

Mission Objectives

To explore Europa, investigate its habitability and aid in the selection of future landing sites. Europa Clipper will orbit around Jupiter and will have~ 32 flybys as low as 25−100 kilometers to achieve a medium-quality global topographic survey, including ice thickness. Specifically, the objectives are to study:

- Ice shell and ocean: Confirm the existence, and characterize the nature, of water within or beneath the ice,
- Composition: Distribution and chemistry of key compounds and the links to ocean composition.
- Geology: Characteristics and formation of surface features, including sites of recent or current activity.

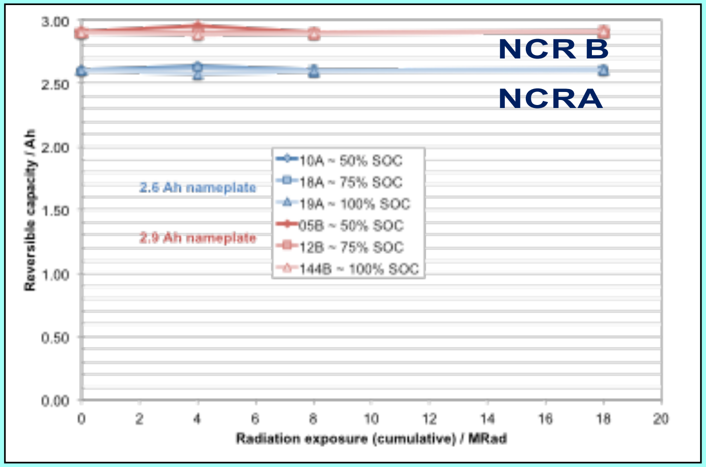


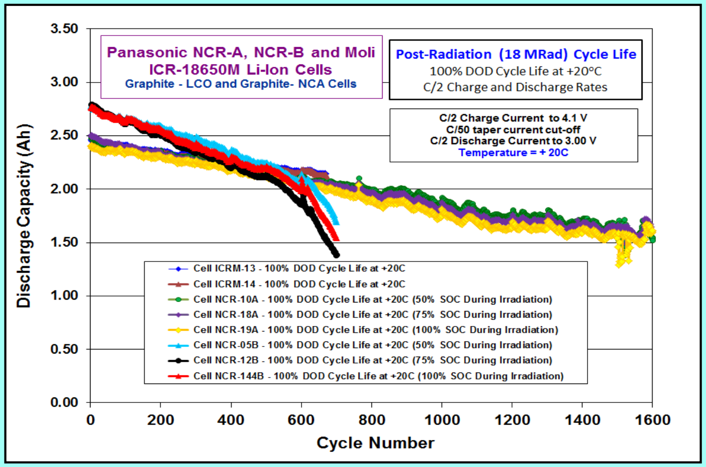
Mission Summary (JPL/APL)

- Launch date: NET 2022
- Launch vehicle: Atlas V 551 or SLS[3]
- Mission duration: Cruise: 6.4 years
- Science: 3.5 years[5]
- Orbits : 32 to 48
- Power: Solar cells (450 W). Solar panels of $90m^2$, challenges: Radiation, Low Intensity and Low Temperature (LILT)
- Batteries: 3 x 8S72P Li-ion batteries (30V, 330 Ah) (E-One Moli M cells)

Europa Clipper Li-Ion Battery Technology Validation Testing

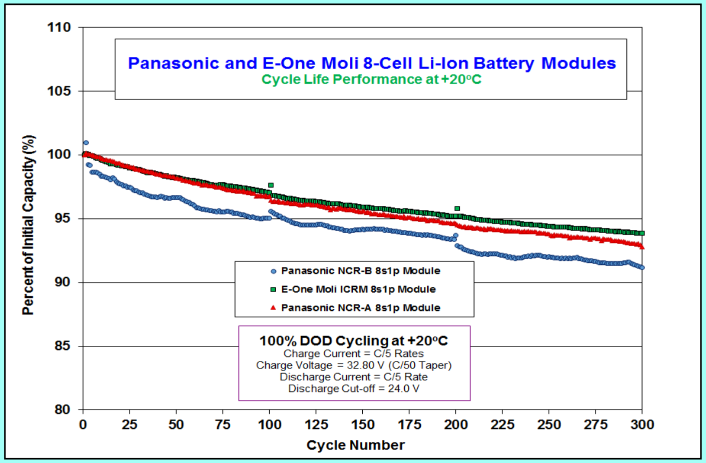
Capacity after 18 Mrad of ^{60}Co irradiation

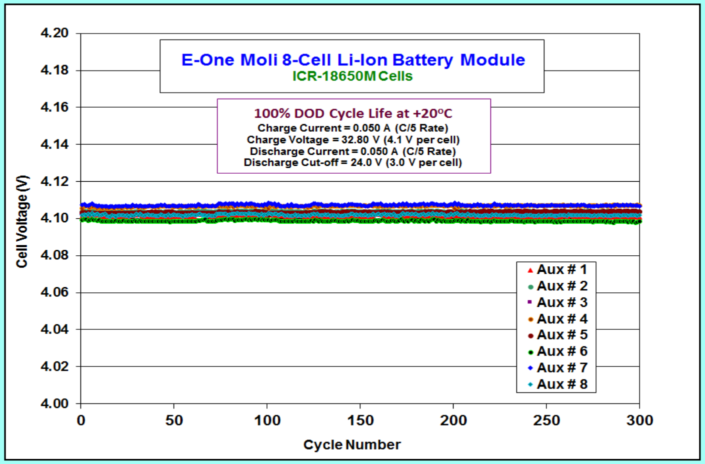




Cycle life after 18 Mrad of ^{60}Co irradiation

Module Cycling at 0C

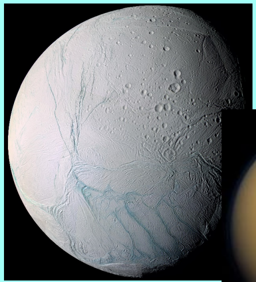




Module cycling – Cell Dispersions

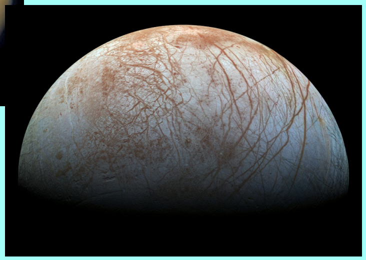
Life Beyond Earth – In Ocean Worlds

- Planetary Habitats Theme: “Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?”



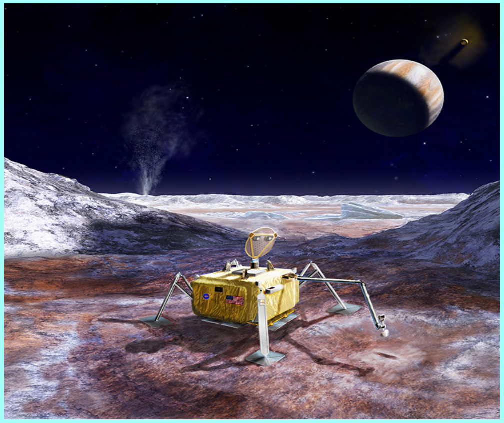
Enceladus

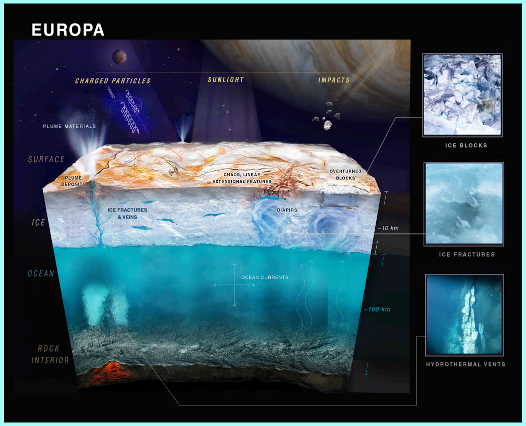
Titan



Europa

Europa Lander Mission (Concept)

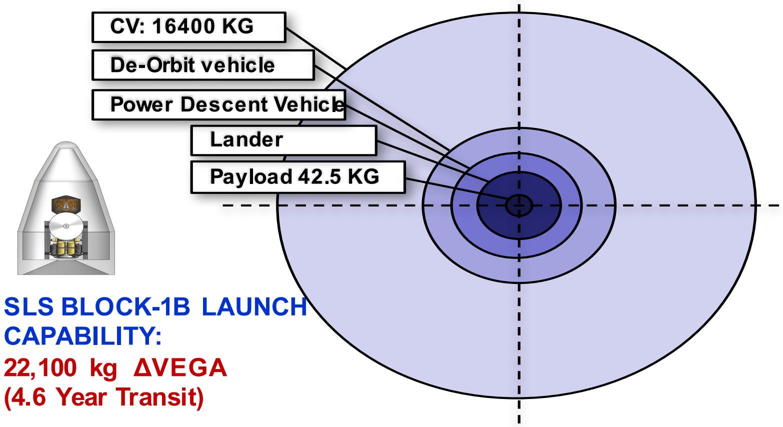




Four Significant Challenges

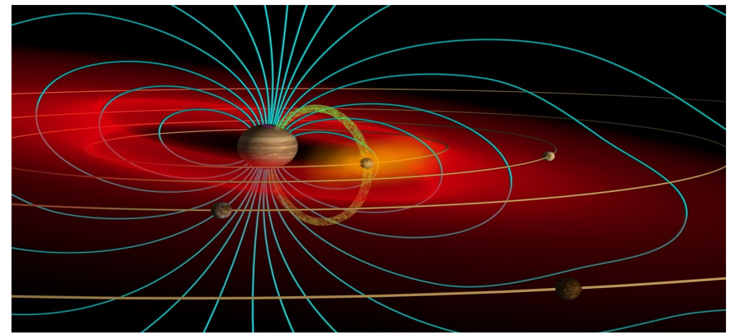
What makes the Europa Lander more challenging than Mars or Lunar landers

1 - Launch Mass:



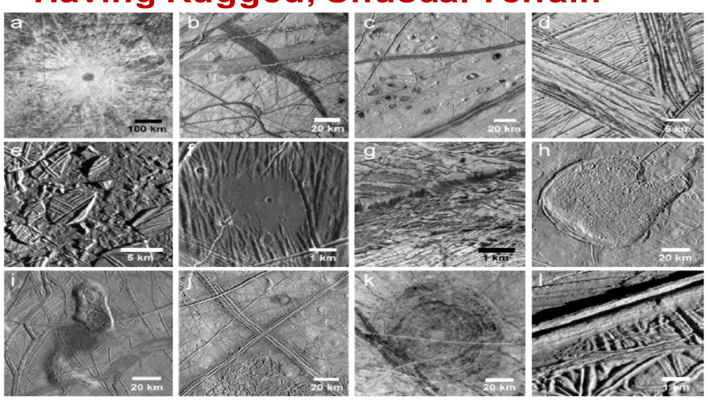
SLS BLOCK-1B LAUNCH CAPABILITY:
22,100 kg ΔVEGA
(4.6 Year Transit)

3 - Jovian Radiation Environment:



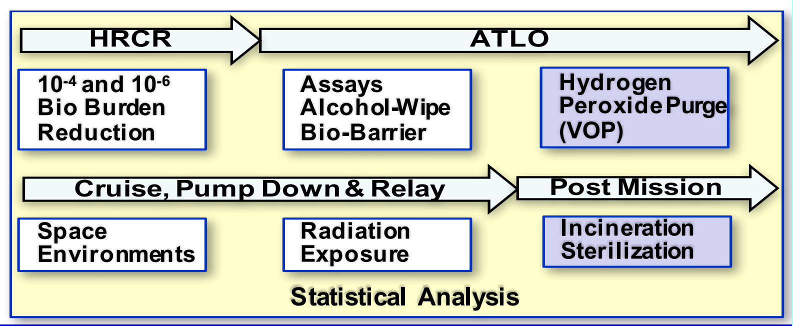
- Drives short surface mission duration ~ 30 day Relay Orbiter
- Vaults provide a 150 kilo-rad environment with a RDF of 2.0

Galileo Images Show Europa Having Rugged, Unusual Terrain



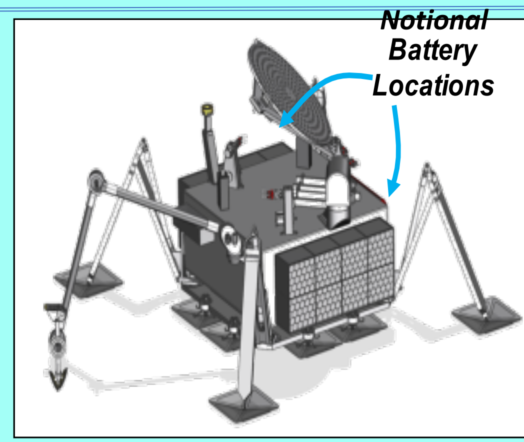
4 - Planetary Protection:

Europa Lander must have a less than 10^{-4} probability of introducing a single "Viable Organism" to any Europa habitable zones – Drives ATLO

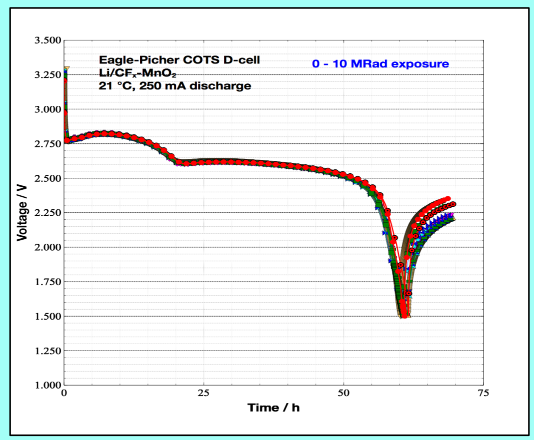


Europa Lander Mission Concept Enabled by LI-CF_X

- 500 Wh/kg at the battery level to support 20-day mission (low discharge rate)
- Li-CF_X chemistry has been demonstrated to meet these requirements
  - High electrical energy density (730 Whr/Kg)
  - Significant battery self heating keeps battery and vault warm
- Battery temperature 0 to +60^{o}C
- 90 kg battery mass allocation
- Power: 50 -600 mA/cell
- Challenges
  - Radiation tolerance and planetary protection
  - Space qualification

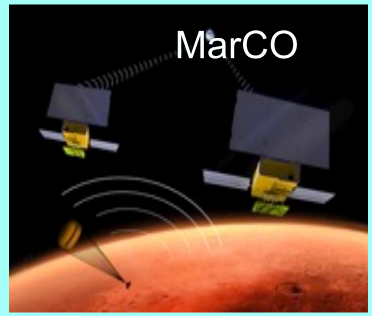


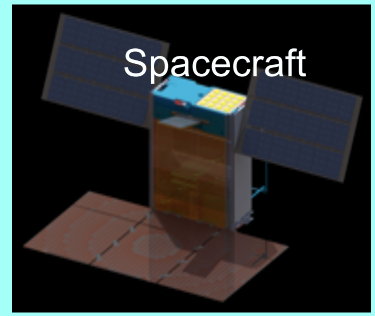
Cell Chemistry	Cell Specific Energy (Wh/kg)	Vendor(s)	Flight Heritage
Li/SO_2	270	Saft	Huygens, Galileo Probe
$LiSOCl_2$	350	Saft	MER, Deep Impact
Li/MnO_2	210	Saft, Ultralife	None
Li/CF_x-MnO_2	560	Eagle-Picher	None
Li/CF_x	730	Ray-O-Vac, Eagle-Picher	None



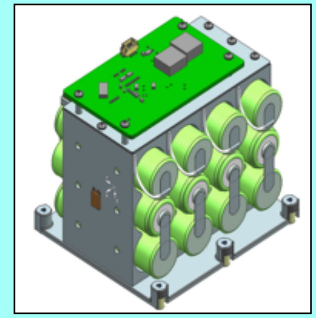
Mars Cube One (MarCO)

- The twin communications-relay CubeSats, constitute a technology demonstration called Mars Cube One (MarCO) on InSight.
  - A Technology Demonstration of communications relay system for mission-critical events such as the 2016 InSight entry, descent, & landing.
- The basic CubeSat unit is a box roughly 4” square.
- MarCO's design is a six-unit CubeSat, with a stowed size of about 14.4” x 9.5” X 4.6”
- The redundant 6U CubeSats will separate from the Atlas V booster after launch and travel along their own trajectories to the Red Planet, independent of the InSight spacecraft, with its own course adjustments on the way.
    - Launch: Mar. 2018; Arrival: Sep. 2016
    - Real-time relay of InSight EDL data
    - 8 kbps UHF link: InSight to MarCO
    - 8 kbps X-band link: MarCO to DSN



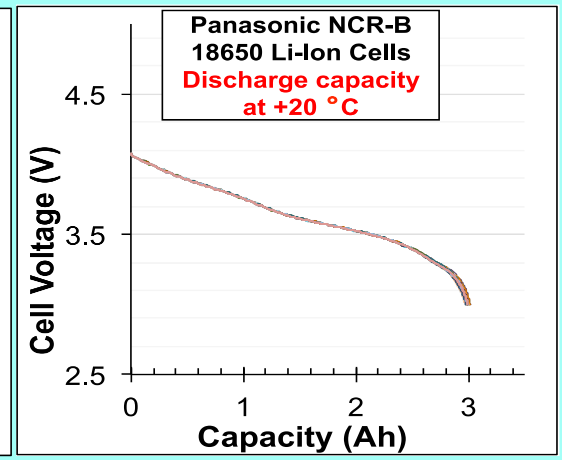


Battery with Panasonic Cells



Cell matching

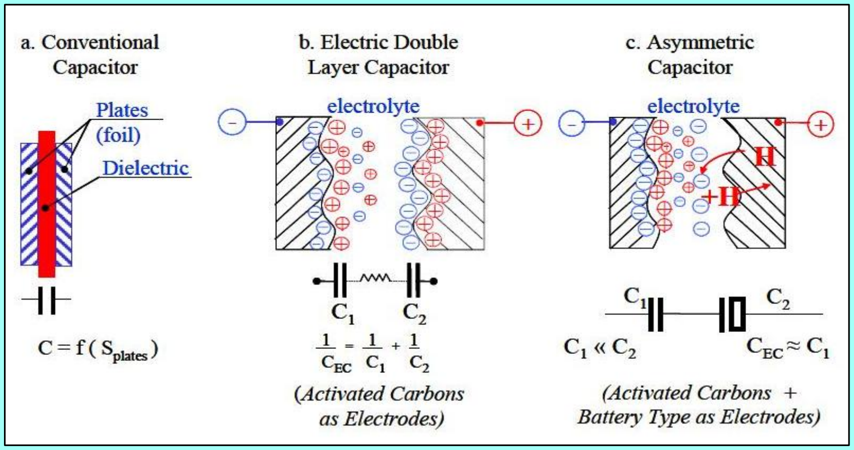
- 20 °C charge/discharge
- 20 °C impedance measurement
- 0 °C charge/discharge
- 0 °C impedance measurement
- Room Temperature 72 hour stand test
- Weighted sum of z-scores



Capacitors

- Umbrella Term: “Electrochemical Capacitors”
  - For <u>bulk</u> energy storage (multi-Farads/low V)
  - vs. electrolytic/dielectric parts (<1 V/high voltage)
- Non-Faradaic (no charge transfer)
  - Electric double-layer capacitor (EDLC)
  - *Supercapacitor*
  - Ultracapacitor
- Faradaic (some charge transfer across electrode)
  - Pseduo-capacitor
  - Asymmetric supercapacitor
  - Li-ion capacitor

Types of Capacitors



Performance Metrics of COTS capacitors

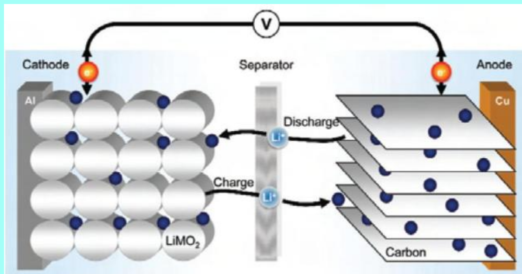
Vendor	Model	Size (F)	Specific Power, kW/kg	Specific Energy, Wh/kg	Max continuous current (A)	Max Peak Current (A)
Maxwell	Boostcap (EDLC)	310-350	4.6-14	5.2-5.9	21-41	170-250
Maxwell	Boostcap (EDLC)	650-3,000	6-12	5	130	2,200
Skeleton	Cylindrical (EDLC)	4,500	24-40	9.6	N/A	3,700
JM Energy	Prismatic (LIC)	3,300	?	13	200	?

Typical Supercapacitor Characteristics

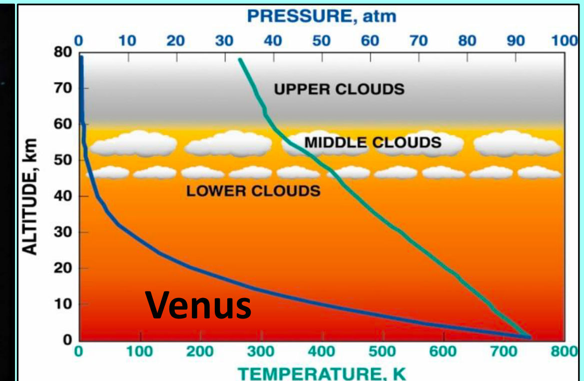
- **Very High Specific Power**
  - Low equivalent series resistance (1-2 mΩ)
  - 5-40 kW/kg
  - Support peak currents of 250 A and continuous currents of 40 A in a typical D-Cell
- **Wide Range of Sizes/Capacities**
  - <1 F to >4000 F (2.5-3.8 V)
- **Wide Temperature Operation**
  - -40 to +65ºC (COTS)
  - -80 to +160ºC (Advanced/Low TRL)
- **Long Calendar/Cycle Life**
  - >10^6 cycles with high pulse power and
  - > 10 years
- **Graceful Degradation**
  - 20% Increase in ESR, 20% decrease in capacitance
- **Insensitive to depth of discharge**
- **Relatively radiation tolerant (initial testing)**
- **Limitations**
  - Low specific energy (5-15 Wh/kg vs. 250 Wh/kg for Li-ion)
  - Relatively high leakage rate (300 µA at 25ºC for typical D-cell)

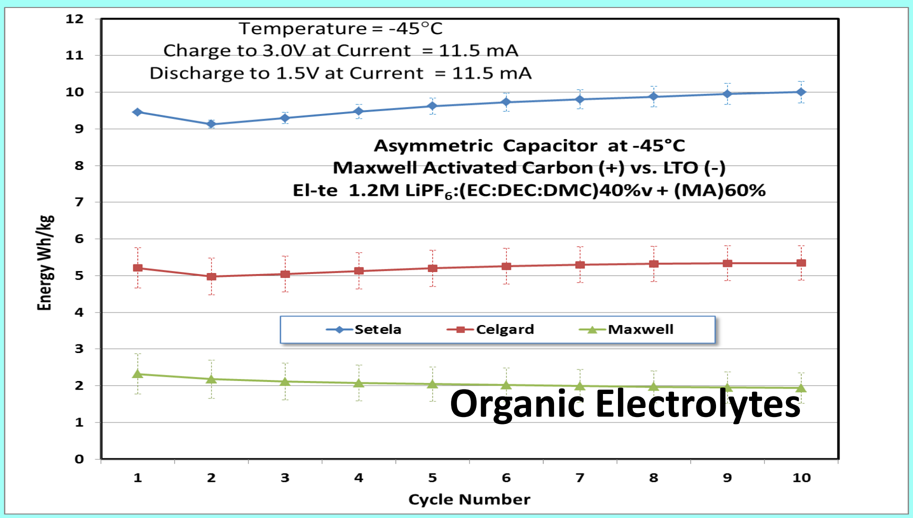
Wide Temperature Capacitors

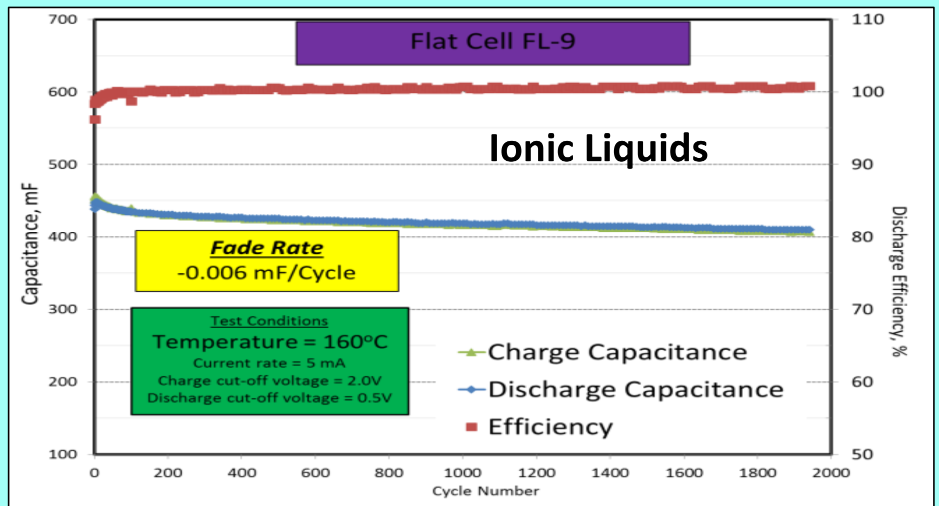
Maxwell Boostcap Supercapacitor with JPL Electrolyte



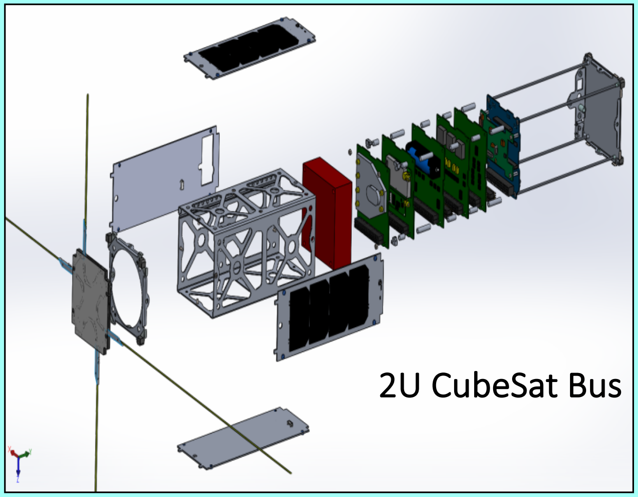
Low Temperature Li-ion Capacitor (JPL/Yardney)

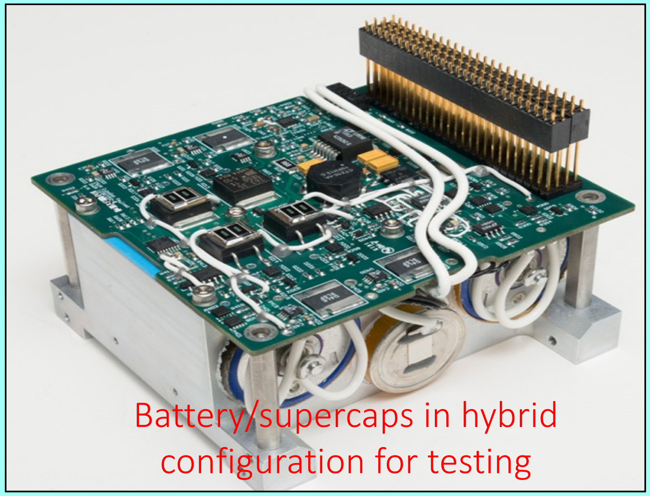


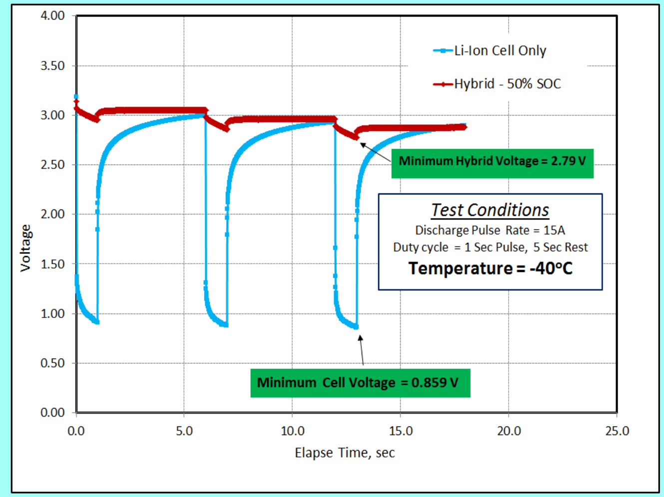




CubeSat Hybrid Power System with CSUN







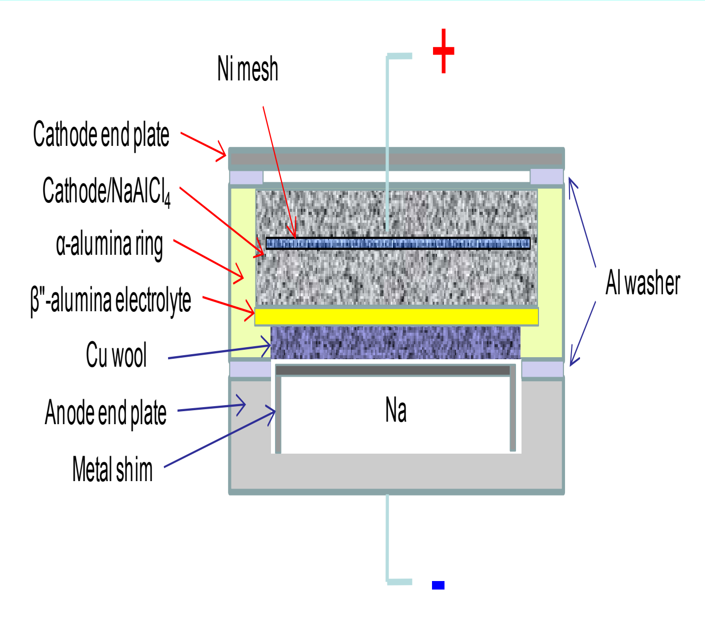
- Earth orbiting mission launched recently from ISS
- Hybrid energy storage payload
- 2U CubeSat
- JPL/Cal State University Northridge collaboration
- Low temperature Li-ion battery and supercapacitor hybrid energy storage system (-40°C)
- Enabler for future deep space missions that require lower temperature capability

High Temperature Rechargeable Batteries for Venus Missions

Based on fused salt electrolyte and/or sodium beta alumina solid electrolyte

Characteristic	$LiAl-FeS_2$	Na-Nickel Chloride	Na-S
Operating Temp Range, °C	400 - 475	220 - 500	290 - 450
Open Circuit Voltage, Volts	1.73	2.58	2.08
Discharge Voltage Range, volts	1.2 –1.8	2.1 to 2.5	1.7 –2.0
Theoretical Specific Energy	490	800	755
Specific Energy for Cells, Wh/kg	90-130	100-130	130-180
Specific Energy for Batteries, Wh/kg	Near 100	90-130	80-120
Energy Density for Cells, Wh/l	150-200	150-190	
Energy Density for Batteries, Wh/l	Near 150	70-130	90-150
Specific Power for Cells, W/kg	90-300		180-390
Specific Power for Batteries, W/kg	Near 150	40-100	100-150
Cycle Life, cycles	>1000	>1000	2000
Energy Efficiency, %	About 80	About 80	About 80

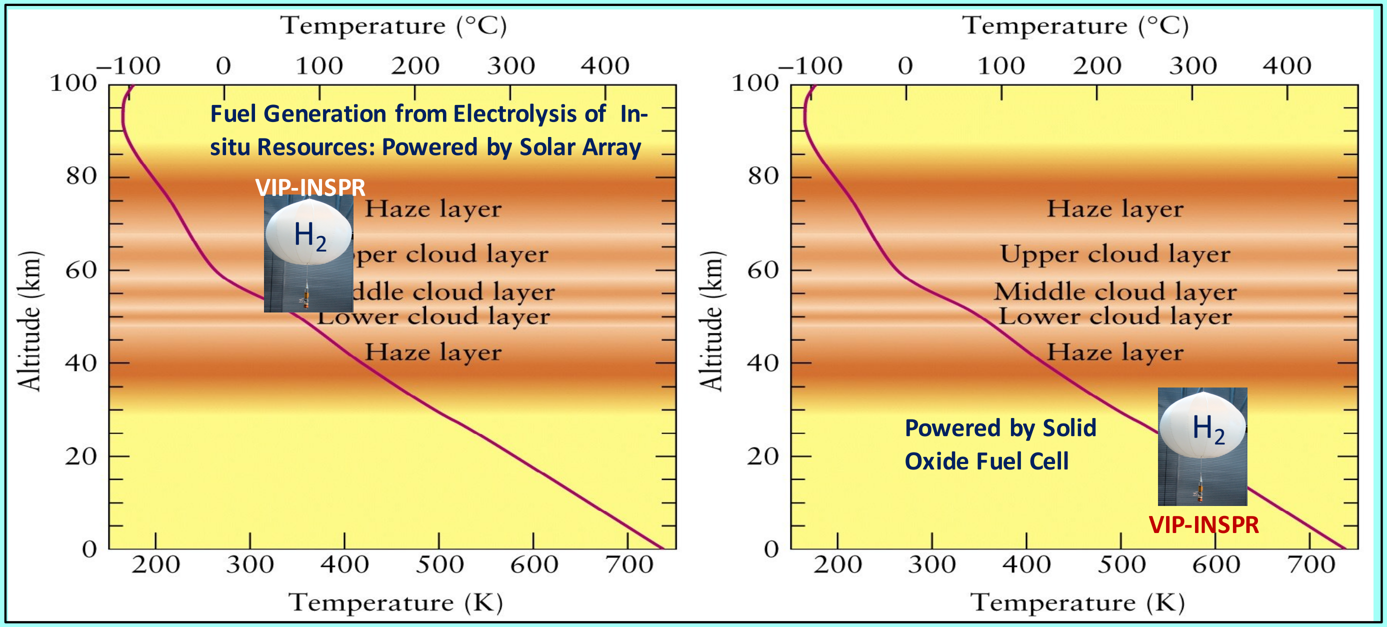
Planar Sodium- Nickel Chloride Cell



New Power Source for Variable Altitude Venus Balloons

Our NIAC (NASA Innovative and Advanced Concept)

- The Venus Interior Probe Using In-situ Power and Propulsion (VIP-INSPR) is a novel architecture for Venus Interior Probe based on in-situ resources for power generation (VIP-INSPR) and navigation.
- This involves the generation of hydrogen and oxygen at high altitude from *in situ* resources, i.e., solar energy and sulfuric acid/water from the Venus clouds and generation of power at low altitudes utilizing these resources in a high temperature fuel cell.
- In addition, the hydrogen generated at high altitudes will also be used as a lifting gas to navigate the probe across the Venus clouds for extended durations (not limited by power).



Acknowledgments

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